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HYDROGEOLOGY AND GROUNDWATER RESOURCES OF THE COLLIE BASIN, WESTERN AUSTRALIA

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HYDROGEOLOGY AND GROUNDWATER RESOURCES OF THE COLLIE BASIN, WESTERN AUSTRALIA

by

S. Varma

Water and Rivers Commission
Resource Science Division

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Copies available from:
Resource Science Division
Water and Rivers Commission
3 Plain Street EAST PERTH
WESTERN AUSTRALIA 6004
Telephone: (08) 9278 0300 Facsimile (08) 9278 0301
http://www.wrc.gov.au

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Cover photograph: Stockton Lake, Collie Basin [taken by S Varma, 2002]

Stockton Lake in the Collie Basin is a disused open cut coal mine that subsequently filled with water. The surface area of the lake is about 15 ha and it is a popular recreation site for activities such as water skiing and swimming. The pH of the lake water varies between 3 and 4.

Acknowledgments

The support provided by the Collie Water Advisory Group and the Collie Basin Research Steering Committee in assessing the hydrogeology and groundwater resources of the Collie Basin is acknowledged. Acknowledgments are due to Western Power Corporation, Griffin Coal Mining Company and Wesfarmers Coal Limited for their support and information during the course of this study.

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Summary

The Collie Basin, in the southwest of Western Australia, contains substantial resources of groundwater that are important for both coal mining and power generation. Groundwater in the basin discharges into the Collie River and its tributaries maintaining the associated environment. An investigation comprising drilling and monitoring of bores has permitted a better understanding of the hydrogeology and groundwater resources of the basin for management of these resources and the associated environment.

The Collie Basin, which forms a northwesterly trending valley in the Darling Plateau has a maximum length of 27 km and a maximum width of about 13 km. It is surrounded by Archaean granitic rocks of the Yilgarn Craton. The surface area of the basin is about 230 km^2. The basin is bilobate in shape and is filled with Permian and Cretaceous sediments having a maximum thickness of 1400 m.

An improved understanding of the hydrogeology of the basin has been developed based on extensive literature review and analysis of drilling, testing and monitoring data. The hydrostratigraphy of the basin has been defined and an aquifer nomenclature proposed. Data were analysed to determine the watertable fluctuations, regional effects of groundwater abstraction, surface water and groundwater interaction, and water balance. The surface water and groundwater balance of the Collie Basin have been established.

Based on data from about 140 monitoring bores in the basin, a synoptic watertable contour map has been prepared, which has enabled the shallow groundwater flow in the basin to be defined. The regional groundwater flow direction in the Collie Basin is highly modified from a conceptual pre-mining flow pattern because of mine dewatering and large-scale groundwater abstraction for power generation. The net groundwater recharge to the basin from direct infiltration of rainfall is estimated as 19 × 10^6 m^3/year. In addition there is 1 × 10^6 m^3/year of recharge from streams flowing into the basin. The recharge to the basin equates to about 10% of the annual rainfall. The volume of abstractable groundwater stored within the basin is about 7100 × 10^6 m^3; however, economics and management policies preclude abstraction at this level. Recharge to each Permian aquifer from the Nakina Formation in the area of the subcrop under pre-mining steady state and present conditions has been estimated using a 3D groundwater model and is provided in the following table.

Recharge to Permian aquifers under pre-mining steady state conditions

Aquifer	*RECHARGE (x10^6 m^3/year)*			
	Cardiff Sub-basin		Premier Sub-basin	
	Pre-mining	Present	Pre-mining	Present
Muja	2.3	5.3	0.3	0.2
Premier	1.9	2.5	1.7	3.5
Allanson	2.9	3.4	0.5	0.7
Ewington	0.4	0.4	0.1	0.2
Westralia	0.3	0.3	0.1	0.1
Stockton	0.5	0.6	0	0.3
Total	**8.3**	**12.5**	**2.7**	**5.0**

Increase in recharge to the Permian aquifers has been induced by large-scale groundwater abstraction. Consequently, groundwater discharge to the Collie River has significantly lessened from an estimated 16 × 10^6 m^3/year to 7 × 10^6 m^3/year.

Although mining in the basin has occurred since 1898, records of groundwater abstraction have been maintained only since 1984. Historical groundwater abstractions in the basin for the period 1898–1983 have been estimated by correlating mine dewatering with annual coal production. In the past, the annual groundwater abstraction from the basin has exceeded recharge, causing a basin-wide decline in groundwater levels. However, since 1995, after closure of the underground mines, water levels in some parts of the basin have been rising. Owing to large-scale abstractions from the Muja Coal Measures in the Cardiff Sub-basin, the watertable is depressed near Collie River South Branch, which directly overlies the abandoned underground mines.

The impact of large-scale groundwater abstraction in the basin on the river pools has been assessed. Data show that the watertable is as much as 5 m below the base of the river bed of some pools. As a result, some pools that were previously maintained by natural groundwater discharge are now dry in summer. It is estimated that it will take some 30 years for the watertable to recover to a level at which pools can be maintained by natural groundwater discharge. Based on the pools' water balance, the pool bed conductances and the water requirements for artificial supplementation have been calculated. Around 2400 m^3/day will be required to maintain water levels in the pools at the cease-to-flow level. Supplementation requirements for each pool are tabulated below.

Summary of pool supplementation requirements

Pool	*Cease-to -flow level (m AHD)*	*Pool Depth# (m)*	*Water requirement (m^3/day)*
Long	183.355	6.54	287-427*
Walkers	182.180	4.18	292-380*
B. Cox	181.238	1.90	46
Cardiff	177.000	3.50	933
Grahams	180.662	3.66	256
Piavininis	176.952	2.91	240
Buckingham Mills	208.000	3.01	47-54*
Total			**2101-2336***

At cease-to-flow level.

* Long, Walkers and Buckingham Mills pools will require more water in summer due to more leakage as a result of lowering of the adjacent watertable.

The groundwater in the basin is mainly sodium chloride type. Groundwater is generally acidic with pH ranging from 2.6 near the underground and opencut mines to 6.3 near the southern and southeastern boundaries of the basin. The acidity of the groundwater is attributed to its contact with sulphide bearing sediments. The groundwater outside the basin has neutral pH.

Groundwater in the basin is fresh, having salinity generally less than 500 mg/L Total Dissolved Solids (TDS). In areas closer to the South Branch in the southern part of Cardiff Sub-basin, where the river level is higher than the watertable, groundwater salinity is between 1000 mg/L and 2000 mg/L TDS. Outside the basin, the crystalline rocks and the overlying lateritic weathered profile mainly contain groundwater having salinity of 1000 mg/L to 17 300 mg/L.

The components of surface-water balance and the groundwater balance of the Collie Basin for 1999–2001 have been determined and summarised in the following tables.

Components of surface-water balance

COMPONENT	*VOLUME (x 10^6 m^3)*	
	1999–2001	*Average per year*
INFLOW		
South Branch catchment yield (granitic terrain)	40	20
East Branch catchment yield	120	60
Mine discharge to South Branch	4	2
Groundwater discharge	14	7
Total inflow	**178**	**89**
OUTFLOW		
Collie River	176	88
Recharge to groundwater from South Branch	2	1
Total outflow	**178**	**89**

Components of groundwater balance

COMPONENT	*VOLUME (x 10^6 m^3)*	
	1999–2001	*Average per year*
INFLOW		
Rainfall recharge	38	19
Stream recharge	2	1
Total inflow (recharge)	40	20 (10%*)
OUTFLOW		
Abstraction	36	18
Groundwater discharge to river	14	7
Evaporation from vegetation	2	1
Total outflow	52	26
Change in storage (inflow-outflow)	**-12**	**-6**

* Percentage of annual rainfall

The historical and current water management issues in the Collie Basin have been discussed in this report, and potential issues for future consideration have been highlighted.

A computer program has been developed in BASIC programming language to simulate the opencut mine void water balance and predict water levels and salinity based on different streamflow diversion options. Water balance modeling of the abandoned Western 5B void shows that with a streamflow diversion of 5 × 10^6 m^3/year the void will overflow in the winter of 2003. Once the void in filled up, about 2 × 10^6 m^3/year of streamflow would maintain the water level in the void near the surface without causing any overflow.

Alternatively, continuation of a streamflow diversion of 5×10^6 m^3/year will result in an overflow of 3×10^6 m^3/year. The water in the mine voids will increase in salinity if streamflow is continually not diverted to the voids. Although, the diversion of water from the South Branch into the voids may reduce the river flows downstream of the voids, it could help recharge the groundwater and, if used for water supply, reduce the demand on the groundwater resources of the basin.

An assessment has been made of the potential discharge of low pH groundwater in the Collie Basin river system as the groundwater level rises, as well as potential overflow of acidic water from the opencut mine voids under certain conditions. The effects of discharge of groundwater of low salinity on the salinity of the Collie River show that the current discharge volumes (7×10^6 m^3/year) cause a reduction of about 7% in the Collie River salinity. Reduction in salinity could be as much as 15% if the groundwater levels in the basin recovered to pre-mining levels. Under increased groundwater discharge conditions, the resultant average pH of the Collie River could reduce from currently neutral to about 6.5. As a result, some toxic pollutants such as As, Be, Cu, Ni, Mo and U, which are present in the Collie Basin coal and able to be mobilised by acidic groundwater, could enter the river. Although, the concentrations of these elements are likely to be low, further research may be required to confirm this and study their downstream impacts.

1 Introduction

1.1 Purpose, scope and methodology

The Collie Basin lies about 160 km south-southeast of Perth, in the southwest of Western Australia, and contains the only producing coal mines in the State (Fig. 1). These provide fuel for generation of about 70% of the electricity that is consumed in the southwest of Western Australia. The basin contains substantial resources of fresh groundwater that are important for both coal mining and power generation. The control of groundwater discharge to the opencut mines is essential to ensure safe and efficient operation. Groundwater from the basin is used for cooling at Muja and Collie power stations. A good understanding of the hydrogeology and groundwater resources of the basin is important for sound management of the groundwater resources and the associated environment.

In 1996, the Collie Water Advisory Group (CWAG), coordinated by the Department of Resource Development, proposed a strategy to upgrade the monitoring bore network to improve the current understanding of the hydrogeology of the basin. This strategy provided for the establishment of an approximate 1.5 km grid of shallow monitoring bores throughout the basin (Collie Water Advisory Group, 1996).

CWAG commissioned a desktop study by consultants Dames and Moore to review the existing network and select additional sites to establish a network of monitoring bores on a 1.5 km grid. Dames and Moore concluded that about 100 additional monitoring bores were required to complete the network, and identified appropriate drilling sites. These included 11 boresites to be drilled by Griffin Coal under groundwater allocation licence conditions applied by the Water and Rivers Commission (Dames and Moore, 1995). CWAG recommended that Water and Rivers Commission coordinate the drilling of the monitoring bores in the Collie Basin and analyse all data to develop a good understanding of the hydrogeology. It was recommended that subsequent monitoring of the bores be carried out by Griffin Coal, Wesfarmers Coal and Western Power Corporation, who are the major users of groundwater in the basin.

As a part of this study the monitoring bore layout proposed by Dames and Moore was reviewed and modified. Modifications in boresite locations were introduced taking into account access to boresites, the need to install some monitoring bores near the Collie River (both South Branch and East Branch), and to avoid areas vulnerable to subsidence. As required by CALM, a botanical survey at each site was carried out to ensure that drilling did not affect endangered flora (Strawbridge, 1997). Achaeological and anthropological surveys were conducted to avoid drilling near sites of Aboriginal heritage (Harris, 1997; Chown et al., 1997).

Montoring bores were constructed by Water and Rivers Commission (WRC) at 80 sites to a maximum depth of 76 m during the months of February, March and April 1998. These bores are known as the Collie Regional Monitoring bores and are denoted by the prefix CRM. A map of the Collie Basin showing all monitoring bores is given in Figure 2. At nine sites, bores could not be constructed due to drilling limitations. Chemical analyses of groundwater samples from the bores were carried out and the quality of the groundwater in the basin has been assessed. A drilling and bore completion report was prepared incorporating the results of drilling and testing (Mohsenzadeh, 1998). A summary of bore data is given in Appendix I.

The geology and hydrostratigraphy of the basin is reviewed and an aquifer nomenclature is proposed. This report provides an understanding of the shallow groundwater flow systems based on extensive literature review and drilling and testing data. Monitoring data were analysed to determine the watertable fluctuations, regional effects of groundwater abstraction, surface water and groundwater interaction, and water balance.

Groundwater recharge to the basin were estimated based on chloride mass balance and water balance. Groundwater discharge in the basin has been assessed and quantified. Estimates of groundwater in storage in the basin have been derived by determining the volume of silt-free sandstone within the Permian units.

An improved understanding of the groundwater flow in the deeper layers of the basin has been achieved using a 3D finite difference groundwater flow model

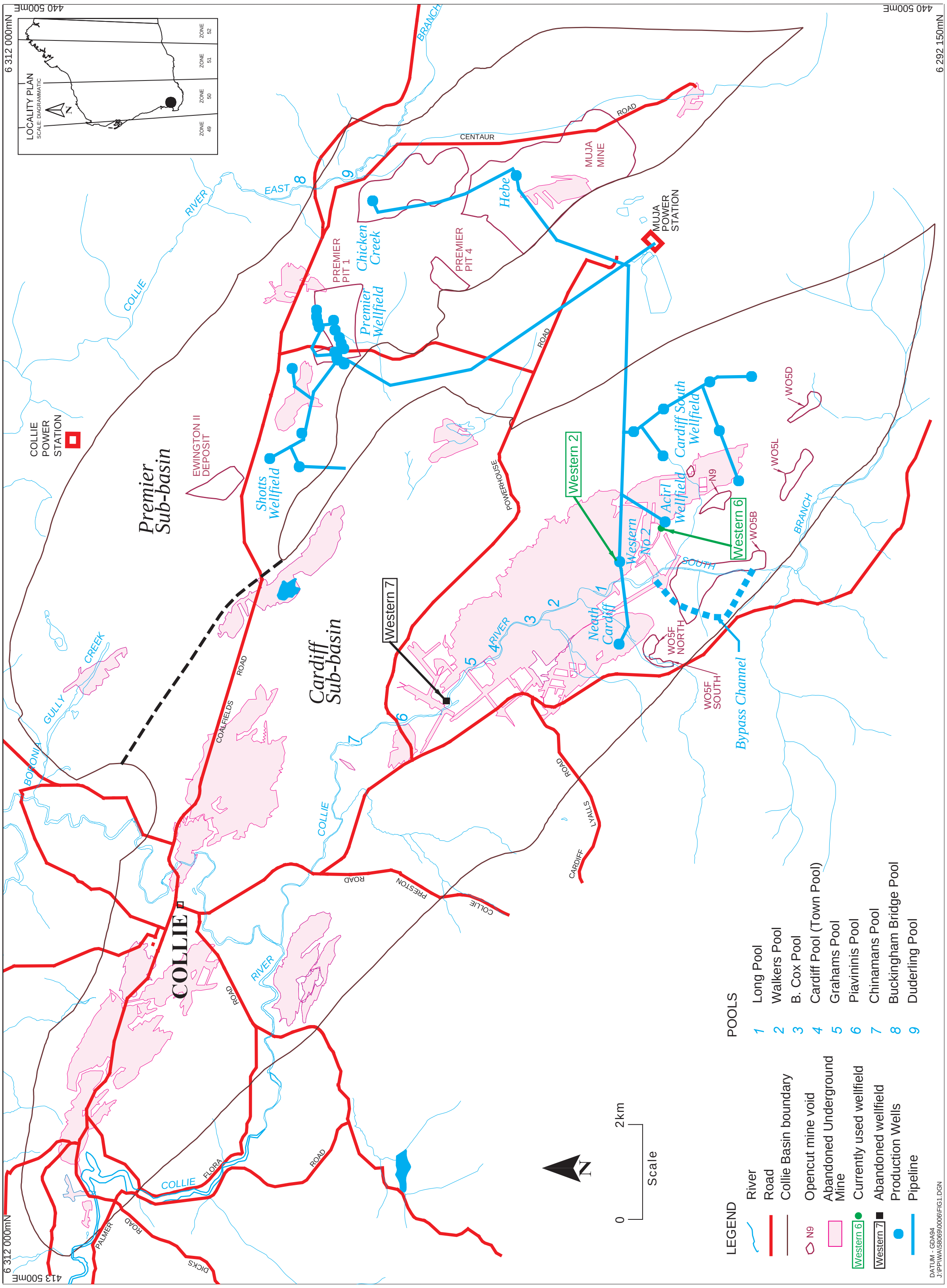


Figure 1. Location

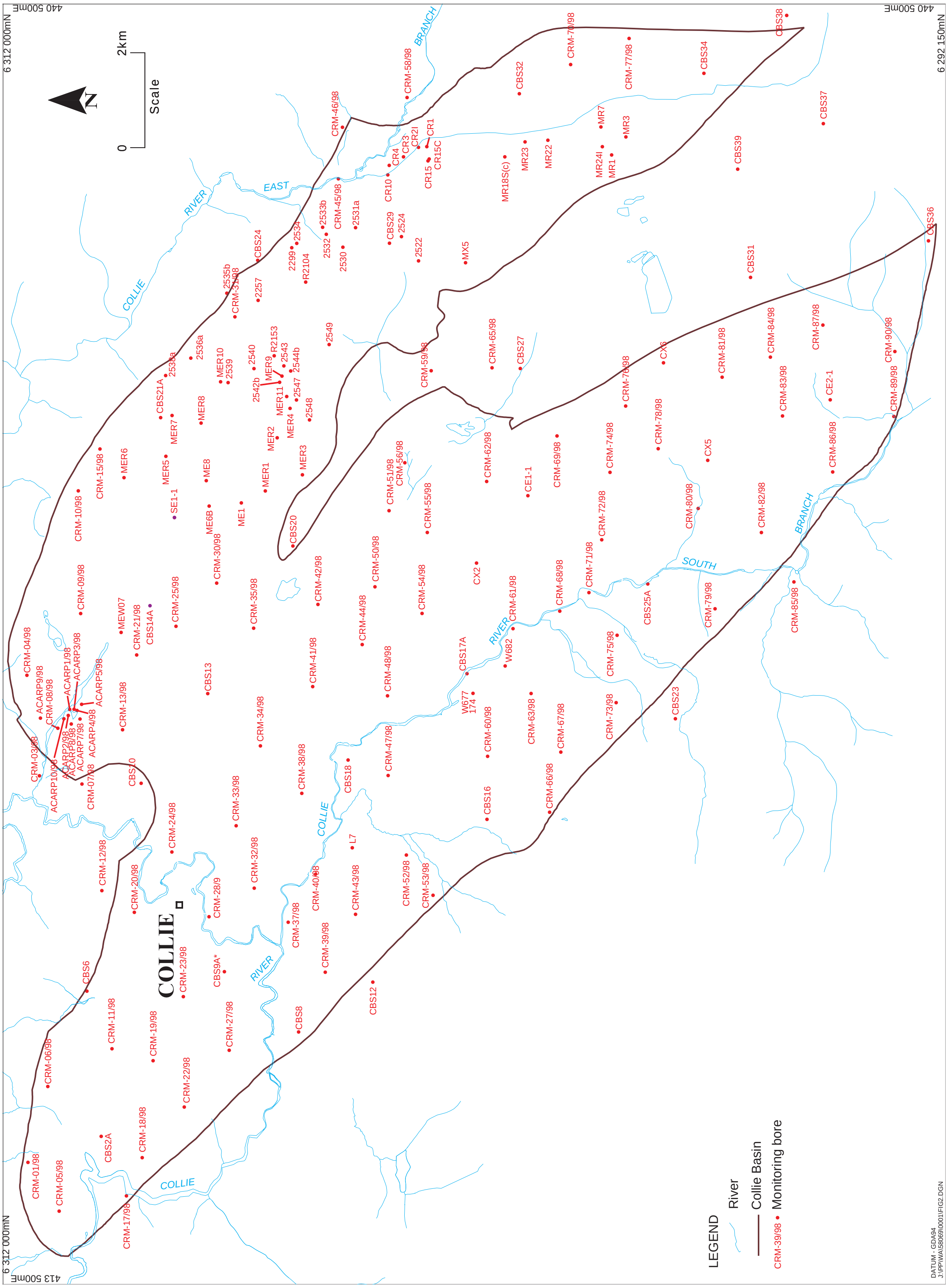


Figure 2. Bore locations

developed by the Water and Rivers Commission (Varma and Zhang 2002).The model has been used to estimate recharge to the Permian Collie Group sediments under pre-mining and present conditions.

Slug-injection and slug-recovery tests were carried out to obtain estimates of hydraulic conductivities of the different sedimentary units in the basin. The results of the slug tests, and tests carried out as a part of previous studies for determination of aquifer parameters have been discussed in this report.

Assessment of the impact of coal mining and groundwater abstraction on the groundwater levels, and on the dependent Collie River South Branch pools, has also been carried out. Monitoring bore hydrographs have been analysed to assess the impact of abstraction from different sedimentary units. Although records of groundwater abstraction in Collie Basin are available only since 1984, annual abstraction prior to this period has been approximated from correlation with coal production data.

The surface-water balance and the groundwater balance of the basin have been established. In some cases where data were not available, for example streamflow volumes for Collie River East Branch, analytical methods have been used to estimate such flows.

The historical and current water management issues in the Collie Basin have been discussed in this report, and potential issues for future consideration have been identified. A water-balance method has been used to determine the stream-bed conductance of the Collie River South Branch at the pools which, in turn, has been used to determine the water requirements for maintaining the pool water levels at different depths. A water balance model of Western 5B opencut mine void has been developed in BASIC programming language. The model can be used to predict water levels and salinity based on different management options, such as use of streamflow diversion for rapid filling of the void. Sample outputs from trial runs of the model have been tabulated.

The results of this study will allow better management of the groundwater resources of the basin in general, and in particular the allocation of groundwater, management of river pools and mine voids.

1.2 Previous studies

The geology of the Collie Basin was first studied in detail by Lord (1952) from drilling of numerous deep bores for coal exploration. Thereafter, general descriptions of the geology of the basin have been provided by Low (1958), Lowry (1976), Wilde (1981) and Wilson (1990).

Hydrogeological studies in the basin have focused mainly on the various mine groundwater-control schemes and power station water supplies, and been described in numerous unpublished reports by consultants. Hirschberg (1976) was the first to undertake a hydrogeological study of the Collie Basin on a regional scale. Australian Groundwater Consultants (1978) investigated the hydrogeology of the basin based on a network of 15 watertable-monitoring bores to determine the availability of the groundwater resources to meet the power station requirements.

Although previous hydrogeological work in the basin gives some indication of the groundwater conditions at that time, the results were based on sparse data and were not able to define the basin hydrogeology.

In 1989, the Geological Survey of Western Australia (GSWA) constructed a network of monitoring bores at 39 sites on a 3 km grid to augment the then monitoring bore network (Moncrieff, 1993). A watertable-monitoring bore was constructed at each site, and at some sites bores were constructed to monitor the piezometric heads at deeper intervals. This work was the first to study the shallow groundwater flow patterns and impact of groundwater abstraction from mines and wellfields. However, owing to the complexity of the geology and hydrogeology of the basin and lack of hydrogeological data, a good understanding of the groundwater flow patterns, recharge to the aquifers, and the extent of impacts from the large-scale abstraction of groundwater was not achieved. Later, a detailed review of the geology and Permian coal resources of the basin was undertaken by GSWA with the results presented by Le Blanc Smith (1993). The report by Le Blanc Smith (1993) is the most recent description of the geology of Collie Basin, and has significantly assisted in developing a better understanding of Collie Basin hydrogeology.

1.3 Physiography

1.3.1 Climate

The Collie Basin has a Mediterranean type climate with hot, dry summers and cool, wet winters. Temperatures can range from below zero on some winter mornings to above 40°C on some summer days. The long-term (100-year) average annual rainfall at the town of Collie is 950 mm (Fig. 3).

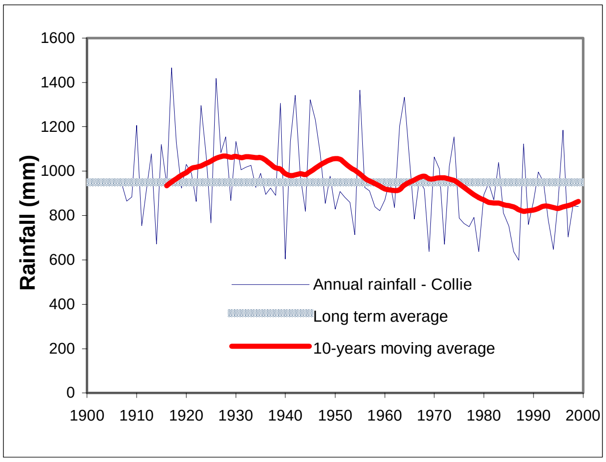


Figure 3. Annual rainfall – Collie Post Office

Average annual rainfall at Collie for the last 20 years is 840 mm. Annual rainfall decreases to the east, being 730 mm as the long-term average and 690 mm as the 20-year average at Muja (Fig. 4). About 75–80% of the annual rainfall take place during the months of May to September. The 10-year moving average rainfall for Collie shows a 20–22 years cycle of high and low rainfall, with a gradually declining overall trend. The annual rainfall for the area of the Collie Basin is taken as the mean of the data from the Collie Post Office and Muja. The average annual potential evaporation at Collie is likely to be about 1650 mm based on data from Wokalup (Bureau of Meteorology, 1998).

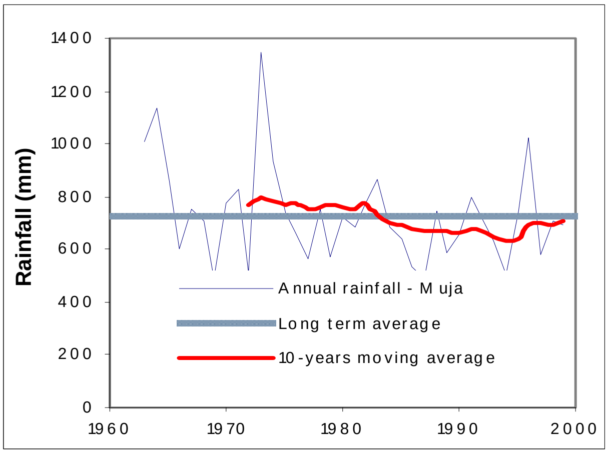


Figure 4. Annual rainfall – Muja

1.3.2 Geomorphology

The Collie Basin forms a northwesterly trending valley in the Darling Plateau, having a maximum length of 27 km and a maximum width of about 13 km. It is surrounded by Archaean granitic rocks of the Yilgarn Craton. The surface area of the basin is about 230 km^2. It is bilobate in shape and is filled with Permian to Recent sediments.

The shape of the basin was first determined by gravity survey by Chamberlain (1947) and later revised by Kevi (1990) (Fig. 5). The southwestern and northeastern lobes of the basin are known as the Cardiff Sub-basin and Premier Sub-basin respectively, and are separated by a basement high known as the Stockton Ridge. Work involving studies of mine exposures, geotechnical analyses and mapping of drillhole core have revealed that the basin structure is associated with basement fault movement (Joass, 1990 and Bogacz, 1992, *in* Le Blanc Smith, 1993).

The topographical gradient is towards the northwest with elevations ranging from 250 m AHD (Australian Height Datum) along the southwestern and southeastern margins of the basin to 160 m AHD in the northwest (Fig. 6). Hills of the Darling Range surrounding the basin reach an elevation of about 350 m AHD. The surface of the basin is gently undulating with wide flat valleys and ridges having smooth rising flanks, except where they are laterite capped and form escarpments. The low-lying areas generally have wetlands that include streams, creeks and swamps. Some abandoned opencut mines have formed lakes such as the Stockton Lake.

1.3.3 Drainage

The Collie Basin is drained by the northwest-flowing Collie River and its two major tributaries, the South Branch and the East Branch. Numerous creeks traverse the basin, eventually discharging into the South Branch or the East Branch. Discharge of excess water from mine dewatering contributes to additional flow in the South Branch and the East Branch.

During summer, there is generally no flow in the South Branch downstream of Piavininis Pool and in the East Branch to the east of the basin boundary. The mean annual flow in the South Branch at gauging station S612034 is 30.5×10^6 m^3 and is 27% of the mean flow in the Collie River at Mungalup Tower gauging station (S612002). The flow in the East Branch at gauging

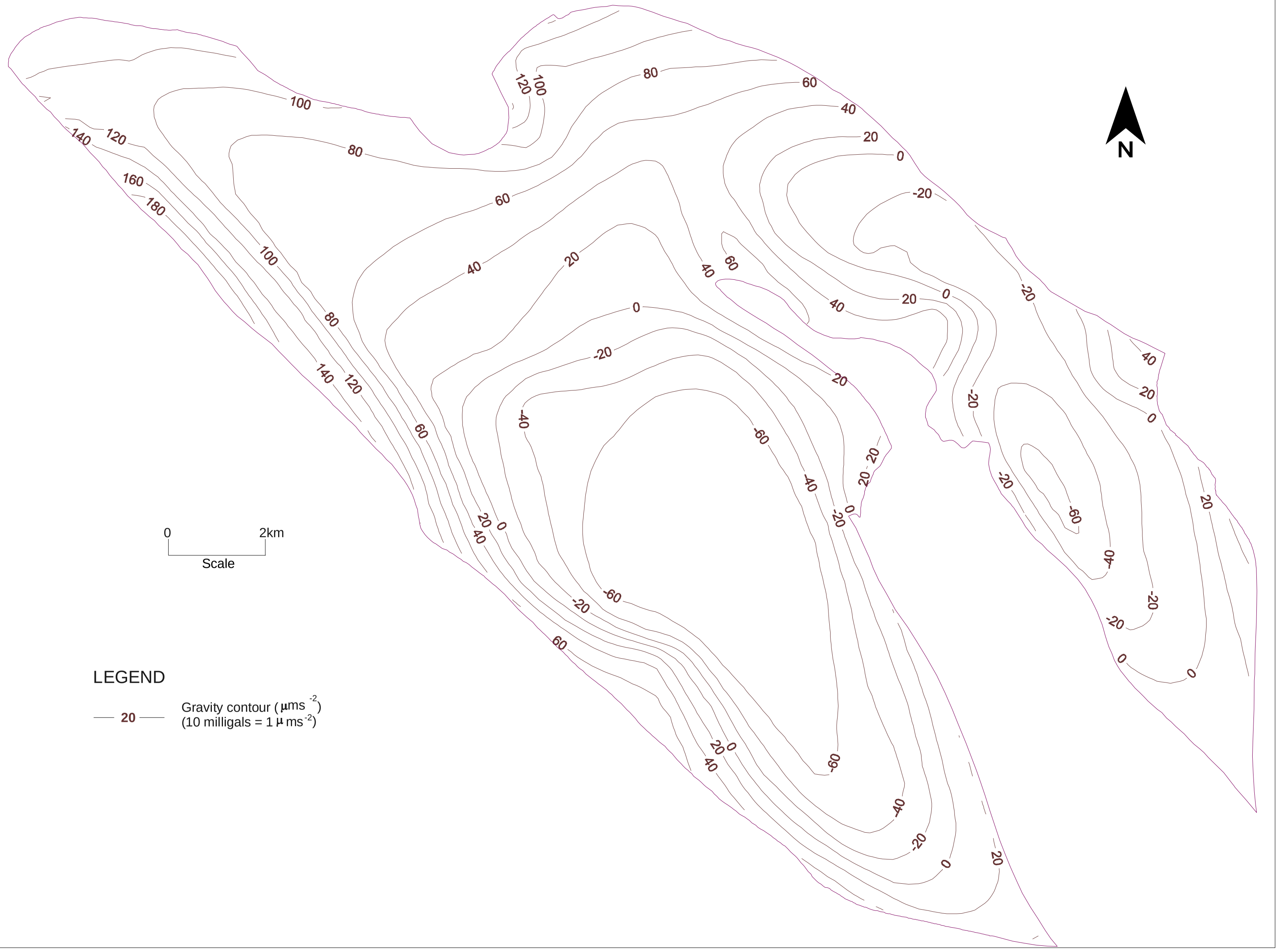


Figure 5. Gravity anomaly of the Collie Basin

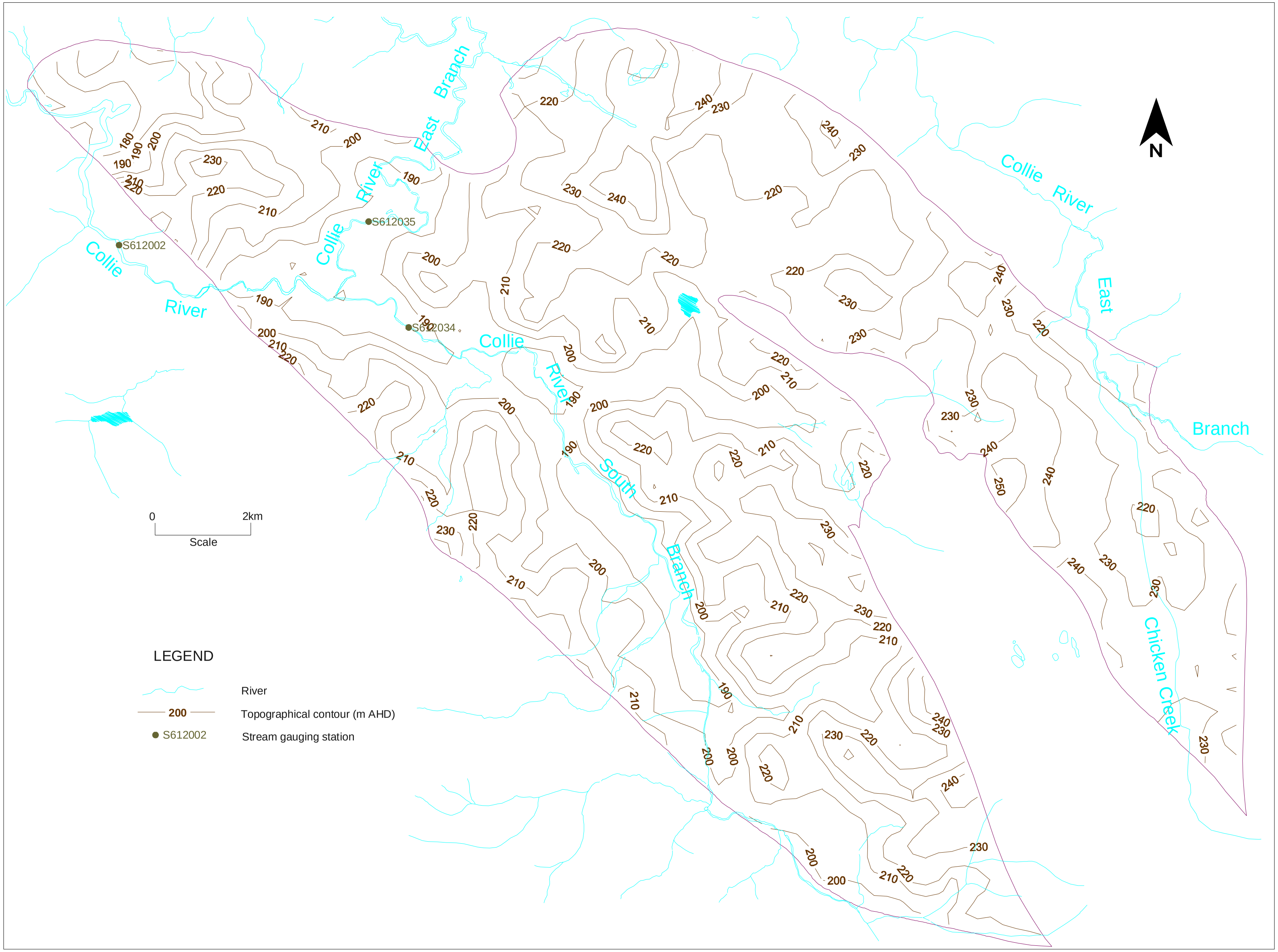


Figure 6. Topography and drainage

station S612035 has been recorded intermittently between 1952 and 1976. However, recent annual flows in the East Branch have been analytically estimated from correlation of flows at other gauging stations within the catchment. Ephemeral flow also occurs in Chicken Creek in the southeast of the basin and Boronia Gully in the north, both draining into the East Branch.

The salinity of water in the South Branch ranges between 1000 mg/L and 1500 mg/L and is about 10% greater than the salinity in the Collie River. Salinity in the pools of South Branch is about 2000–2500 mg/L. Salinity in Chinamans Pool on the downstream part of the South Branch, however, is less than 500 mg/L. The pools of the East Branch in the southeastern part of the basin have salinity in the range of 3000–4500 mg/L.

2 Geology

2.1 Overview

The Collie Basin consists of Permian to Recent sedimentary deposits overlying the Archaean crystalline rocks.The Permian sediments of the basin are classified under the coal-bearing Collie Group and the glacial Stockton Group. These sediments subcrop beneath the laterally extensive Cretaceous Nakina Formation, and have a predominant southwesterly dip. The geology of the Premier and Cardiff Sub-basins is similar in stratigraphic sequence and the sedimentary units are correlatable within the two sub-basins. Maximum thickness of the Permian sediments is about 1400 m in the Cardiff Sub-basin and about 750 m in the Premier Sub-basin and is based on correlation of several deep exploratory drillholes. However, the drillholes have not penetrated the basement in the deeper parts of the basin and the actual thickness of the sediments in the basin is uncertain. Quantitative interpretation of the Bouguer anomaly calibrated with the wireline density logs could provide a better understanding of the basin at depth. Several northwesterly faults traverse the basin and predate the deposition of the Nakina Formation. Faulting in the basin has been described in detail by Le Blanc Smith (1993). The faults are believed to have been caused by a series of tectonic block movements. Low-amplitude folding in the strata is associated with common dip-slip faults (Geo-Eng, 2000). The stratigraphy of the Collie Basin is summarised in Table 1. Schematic structural cross sections of the Collie Basin are presented in Figure 7. Maximum thicknesses of the Permian sedimentary units have been derived from interpolation and extrapolation of the geological contacts from drill logs of deep exploratory bores using ‘Surfer’ contouring package (Geo-Eng, 2000).

The following sections provide a summary of the stratigraphic units of the Collie Basin based on the work of several authors. The most comprehensive detail has been provided by Le Blanc Smith (1993). Geo-Eng (2000) digitised geological contacts from the borehole data and published literature, and prepared contours of stratigraphic interfaces and isopachs of each sedimentary unit.

2.2 Archaean

The Precambrian basement surrounding the Collie Basin comprises granite and gneissic, schistose and

Table 1. Generalised stratigraphy of the Collie Basin (after Le Blanc Smith, 1993)

AGE	*GROUP*	*FORMATION*	*MAXIMUM*	*THICKNESS*	*LITHOLOGY*
			Cardiff Sub-basin	*Premier Sub-basin*	
TERTIARY TO RECENT	UNGROUPED	Surficial sediments	4 m	4 m	Alluvium, colluvium, laterite
CRETACEOUS		Nakina Formation	20 m	15 m	Sandstone, mudstone
PERMIAN	COLLIE GROUP	Muja Coal Measures	450 m	250 m	Sandstone, minor shale and coal seams
		Premier Coal Measures	600 m	400 m	Sandstone, minor shale and coal seams
		Allanson Sandstone	400 m	300 m	Sandstone
		Ewington Coal Measures	75 m	75 m	Shale, sandstone and coal seams
		Westralia Sandstone	79 m	66 m	Sandstone
	STOCKTON GROUP	Moorhead Formation	370 m	50 m	Mudstone and tillite
		Shotts Formation			Gravel conglomerate and basement clasts, sandstone
ARCHAEAN					Granite, dolerite, metasediments

doleritic rocks. Mafic rocks are common. Recent drilling intersected the basement within a depth of 15 m at bore sites CRM-02, CRM-03, CRM-07, CRM-12, CRM-59 and CRM-65 near basin boundaries. The Stockton Ridge forms a basement high dividing the basin into the two sub-basins and is composed of granitic rocks that contain numerous dykes. The maximum thickness of sediments overlying the Stockton Ridge is about 80 m at the northwestern end of the ridge.

2.3 Permian

2.3.1 Stockton Group

The Stockton Group is of Early Permian age and is defined as comprising the Shotts Formation and the Moorhead Formation. Its thickness ranges from more than 370 m in the deeper parts of the Cardiff Sub-basin to less than 50 m near the Stockton Ridge and in the Premier Sub-basin. The Stockton Group was deposited in a glacial setting.

2.3.1.1 Shotts Formation

The Shotts Formation rests unconformably on crystalline rocks of the Yilgarn Craton and consists of tillite with extrabasinal clasts, gravel conglomerate, poorly sorted pebbly sandstone and thin shale. A type section in a coal exploratory drillhole contained about 36 m of this unit.

2.3.1.2 Moorhead Formation

The Moorhead Formation conformably overlies the Shotts Formation and consists of laminated claystone with thin beds of siltstone, fine-grained sandstone, and rare limestone lenses. The thickest section of this unit is 230 m in an incomplete penetration in an exploratory bore.

2.3.2 Collie Group

The Collie Group conformably overlies the Stockton Group and comprises the coal-bearing Permian sediments of the Collie Basin. The maximum thickness of the Collie Group sediments is some 900 m at the southwestern boundary of the Cardiff Sub-basin and about 750 m at the southwestern edge of the Premier Sub-basin; thinning occurs towards the northeastern margins of the sub-basins. The Collie Group comprises a number of distinct units that are named Westralia Sandstone, Ewington Coal Measures, Allanson Sandstone, Premier Coal Measures and Muja Coal Measures in a ‘younging up’ sequence. The Collie Group consists mainly of sandstone with some shale, mudstone and coal.

2.3.2.1 Westralia Sandstone

The Westralia Sandstone comformably overlies the Moorhead Formation of the Stockton Group and comprises predominantly sandstone that shows an upward coarsening sequence. The maximum thickness intersected is 79 m in the northwestern part of the Cardiff Sub-basin. Elsewhere, the thickness ranges between 30 m and 50 m. The Westralia Sandstone does not contain any coal seams, but is bounded from above by the stratigraphically lowest coal seam of the Ewington Coal Measures. The depositional environment was proglacial lacustrine delta.

2.3.2.2 Ewington Coal Measures

The Ewington Coal Measures rests comformably on the Westralia Sandstone and consists of felspathic sandstone, carbonaceous shale, clast-supported conglomerate, and coal. Coal seams range from a few centimetres to 5 m in thickness and are areally extensive. The maximum thickness of the Ewington Coal Measures is 75 m near the southwestern edges of the two sub-basins, and gradually thins towards the other boundaries. The depositional environment was a proglacial lacustrine delta.

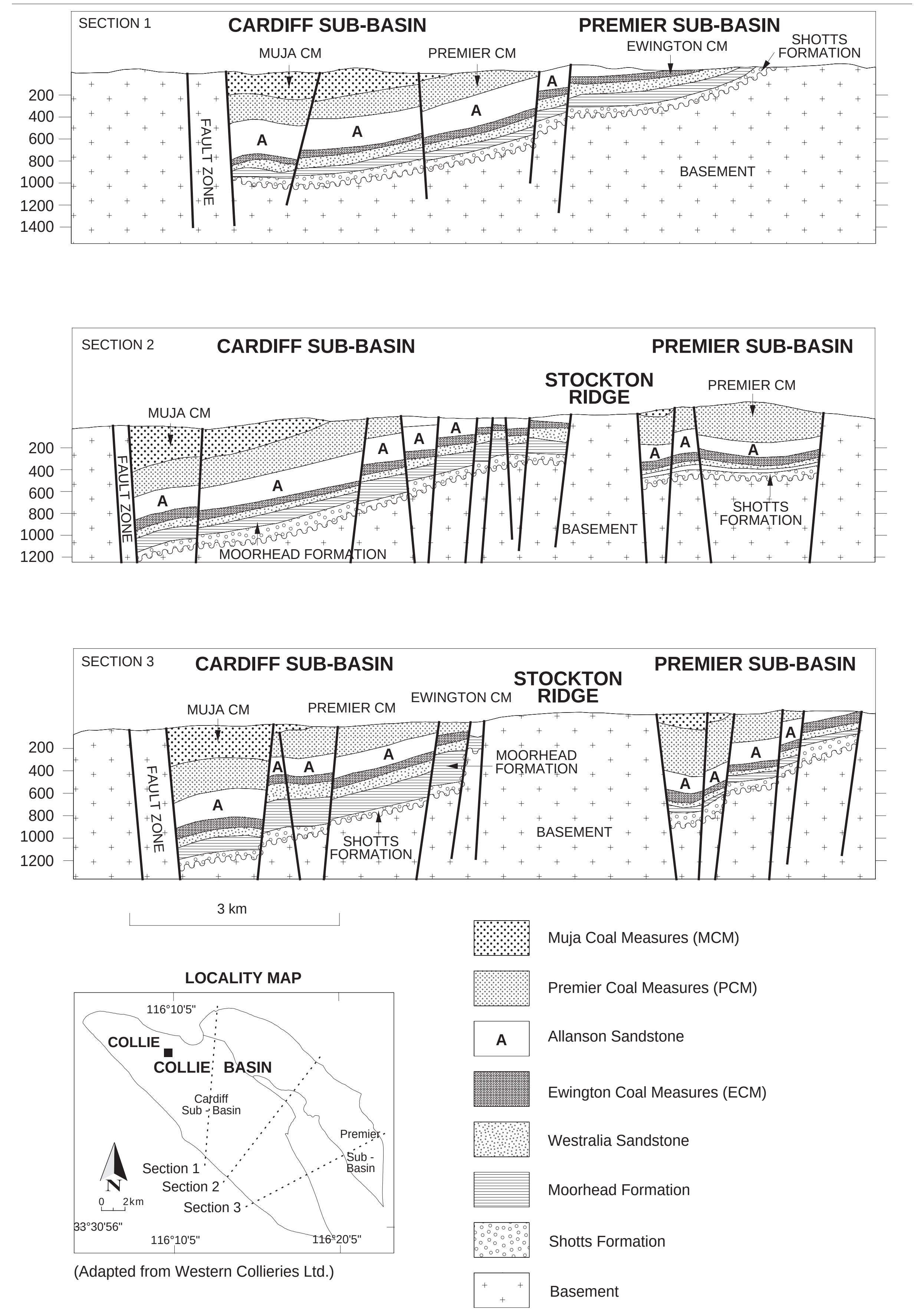
2.3.2.3 Allanson Sandstone

The Allanson Sandstone lies conformably above the Ewington Coal Measures. The unit is mostly devoid of coal seams with the exception of a few such as the Hymen Seam, which is up to 1.5 m thick.

The unit generally consists of fine to coarse grained sandstone, siltstone and mudstone. Thickness varies from 300 m to 400 m in the southwestern margins of the two sub-basins, gradually thinning towards the other boundaries. The unit is absent in the northwestern and southeastern parts of the sub-basins and in the area of the Stockton Ridge. The Allanson Sandstone was deposited in an alluvial-plain setting.

2.3.2.4 Premier Coal Measures

The Premier Coal Measures consists of intebedded sandstone, shale, conglomerate and coal, and lies conformably above the Allanson Sandstone. The sandstone is generally fine to medium grained. The unit occurs only in the central part of the sub-basins and is up to 600 m thick in Cardiff Sub-basin and reaches 400 m in Premier Sub-basin. The Premier Coal Measures was deposited in an alluvial-plain setting.



(Adapted from Western Collieries Ltd.)

Figure 7. Schematic structural cross sections of the Collie Basin (from GSWA Report 38)

2.3.2.5 Muja Coal Measures

The Muja Coal Measures comprises sandstone and siltstone intercalated with numerous coal seams that are up to 15 m thick. The unit has a maximum thickness of about 450 m in the Cardiff Sub-basin and 250 m in the Premier Sub-basin. It is present only in the central part of the Cardiff Sub-basin and abuts the Precambrian rocks at the edge of the sub-basin, and at the southwestern edge of the Premier Sub-basin. The Muja Coal Measures was deposited in an alluvial-plain setting.

2.4 Cretaceous

2.4.1 Nakina Formation

The Nakina Formation unconformably overlies the Collie Group sediments and extends throughout the basin. This formation consists of an upwardly fining cycle of claystone, sandstone and conglomerate, with an erosional base. The maximum encountered thickness of the Nakina Formation is about 20 m. It is believed that the depositional environment of the Nakina Formation was freshwater fluviolacustrine. Owing to erosion, the Nakina Formation may be thinner beneath the rivers and on the ridges. Figure 8 shows the contours of the base of the Nakina Formation with subcropping Permian sediments.

2.5 Tertiary to Recent

The Tertiary to Recent deposits comprise laterite, alluvium and colluvium that form the surficial sediments overlying the Nakina Formation and have a maximum thickness of 4 m. Laterite caps the ridges, whereas alluvium and colluvium cover the low-lying areas. The laterite, developed over sedimentary rocks in the basin, is generally sandy. Alluvium and colluvium are present near valleys. These deposits have a maximum thickness of 4 m but are commonly less than 2 m thick.

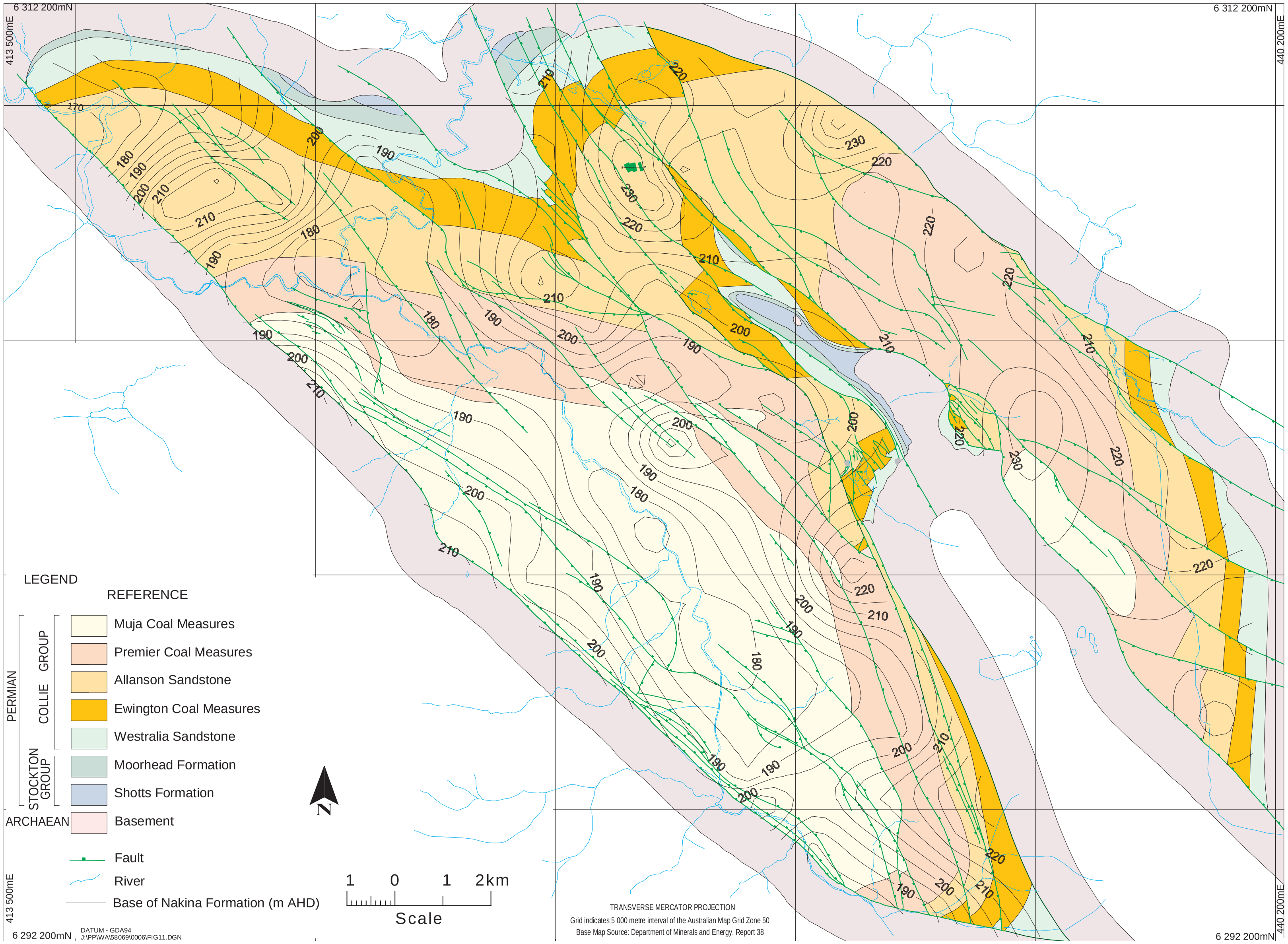


Figure 8. Contours of the base of Nakina Formation with strata subcrop

3 Hydrogeology

3.1 Groundwater occurrence/ hydrostratigraphy

The hydrogeology of the Collie Basin is complex. Until now, a good understanding of the hydrogeology of the basin on a regional scale was not possible owing to lack of sufficient drilling, testing and monitoring data. As a part of this investigation, the drilling of additional monitoring bores in 1998, to establish a closer monitoring network, has made it possible to develop a better understanding of the shallow groundwater flow systems, and identify areas of recharge and discharge. Water level monitoring of bores has helped in developing an improved understanding of the watertable fluctuations, surface water and groundwater interactions, regional and local impacts of groundwater abstraction and dewatering related to mining, and water balance. Owing to a lack of monitoring bores in deeper sediments, it has not been possible to determine the piezometric heads in deeper aquifers and groundwater patterns within these sediments at depth. Groundwater flows in the deeper parts of the basin have, however, been studied using a groundwater model.

Groundwater in abstractable quantities in the Collie Basin is mainly contained within the sandstone of the Muja Coal Measures, Premier Coal Measures, Allanson Sandstone, Ewington Coal Measures and Westralia Sandstone of the Collie Group; within the sand and sandstone of the Nakina Formation; and in the surficial sediments. Some groundwater may also occur in the sandstone of the Shotts Formation. Groundwater flow in the Collie Basin takes place through the pores of the sedimentary units. Porosity is mainly intergranular but fracture porosity also exists at depth (Vogwill and Brunner, 1985 *in* Moncrieff, 1993). Based on an assessment of the lithological logs of some deep production bores in the Cardiff Sub-basin, the aggregate thickness of sandstone is about 70% of the total sediment thickness, and the remaining 30% consists of shale, mudstone and coal seams.

In the past, the coal mining companies have identified the different sandstone beds between individual coal seams as distinct aquifers that have been given the name of the immediately underlying coal seam. While this approach may be appropriate on a local scale when considering dewatering and depressurisation of the water-bearing zones for mining purposes, the use of this nomenclature on a regional scale is not suitable. This is due to the discontinuities of the sandstone beds because of the complexity of the structure that arises mainly from numerous faults that could truncate these sandstone beds over short distances. For the purpose of groundwater resource management on a regional scale, it is more appropriate to lump these sandstone beds into groups of major sandstone layers ideally based on lithostratigraphy as defined by Le Blanc Smith (1993) and separated by extensive confining beds such as coal seams or shale.

With the exception of the Nakina Formation and the surficial sediments, the geological formations form discrete units separated by extensive coal seams or a thick layer of siltstone. Taking this into consideration, seven distinct regional aquifers are proposed for the Collie Basin as shown in Table 2.

The Nakina aquifer comprises the Nakina Formation and the surficial sediments. The Nakina Formation is unsaturated in some parts of the Collie Basin, particularly in areas of major groundwater abstraction and where the formation is thin (Fig. 9). In the Cardiff Sub-basin, areas of unsaturated Nakina Formation occur near the southeastern part where this unit overlies the subcrop zones of the Premier, Allanson and Ewington aquifers, from which abstraction occurs at the Cardiff South wellfield. In the Premier Sub-basin, the Nakina Formation is generally unsaturated in the central and southern parts where large-scale mine dewatering occurs. The watertable is, therefore, mostly within the Collie Group sediments. The Nakina aquifer is unconfined and is in direct hydraulic connection with underlying dipping strata of the Collie Group aquifers.

The Muja, Premier, Allanson, Ewington and Westralia aquifers are formed by the respective Collie Group sediments. The aquifers consist of mainly sandstone with interbedded shale, mudstone and coal seams.

Table 2. Hydrostratigraphy of the Collie Basin

Composite stratigraphic column			
Major unit	**Coal seams**		**Proposed regional aquifer nomenclature**
	Cardiff Sub-basin	**Premier Sub-basin**	
Surficial sediments			
Nakina Formation			**Nakina aquifer**
Muja Coal Measures	Medusa	Ate	**Muja aquifer**
	Niobe		
	Pygmalion		
	Cardiff A	Bellona	
	Cardiff 1		
	Cardiff 2		
	Minos	Ceres	
	Cardiff		
	Neath		
	Abe U	Diana	
	Abe		
	Abe L		
	Ben	Eos	
	Zeus		
	Collieburn 1		
	Orion	Flora	
	Upsilon		
	Alpha		
	Wyvern		
	Rhea	Galatea	
	Rhea L		
	Collieburn 2L	Hebe	
Premier Coal Measures		Premier 1	**Premier aquifer**
	Phoenix	Premier 2	
	Nestor	Premier 3	
	Hermes	Premier 4	
	Acis	Premier 5B	
	Boreas	Premier 6	
	Circe	Juno	
	Icarus	Leda	
	Griffin U	Premier 7	
	Griffin	Tantalus	
	Echo	Premier 8	
	Tantalus	Zephyrus	
	Venus	Eros	
Allanson Sandstone	Hymen	Hymen	**Allanson aquifer**
Ewington Coal Measures	Ewington 1	Ewington 1	**Ewington aquifer**
	Iris	Iris	
	Ewington 2	Ewington 2	
	Moira	Moira	
	Stockton	Stockton	
	Homer	Homer	
	Wallsend	Wallsend	
Westralia Sandstone	No coal seam		**Westralia aquifer**
Moorhead Formation	No coal seam		**Stockton aquifer**
Shotts Formation	No coal seam		
Archaean basement			**Confining basement**

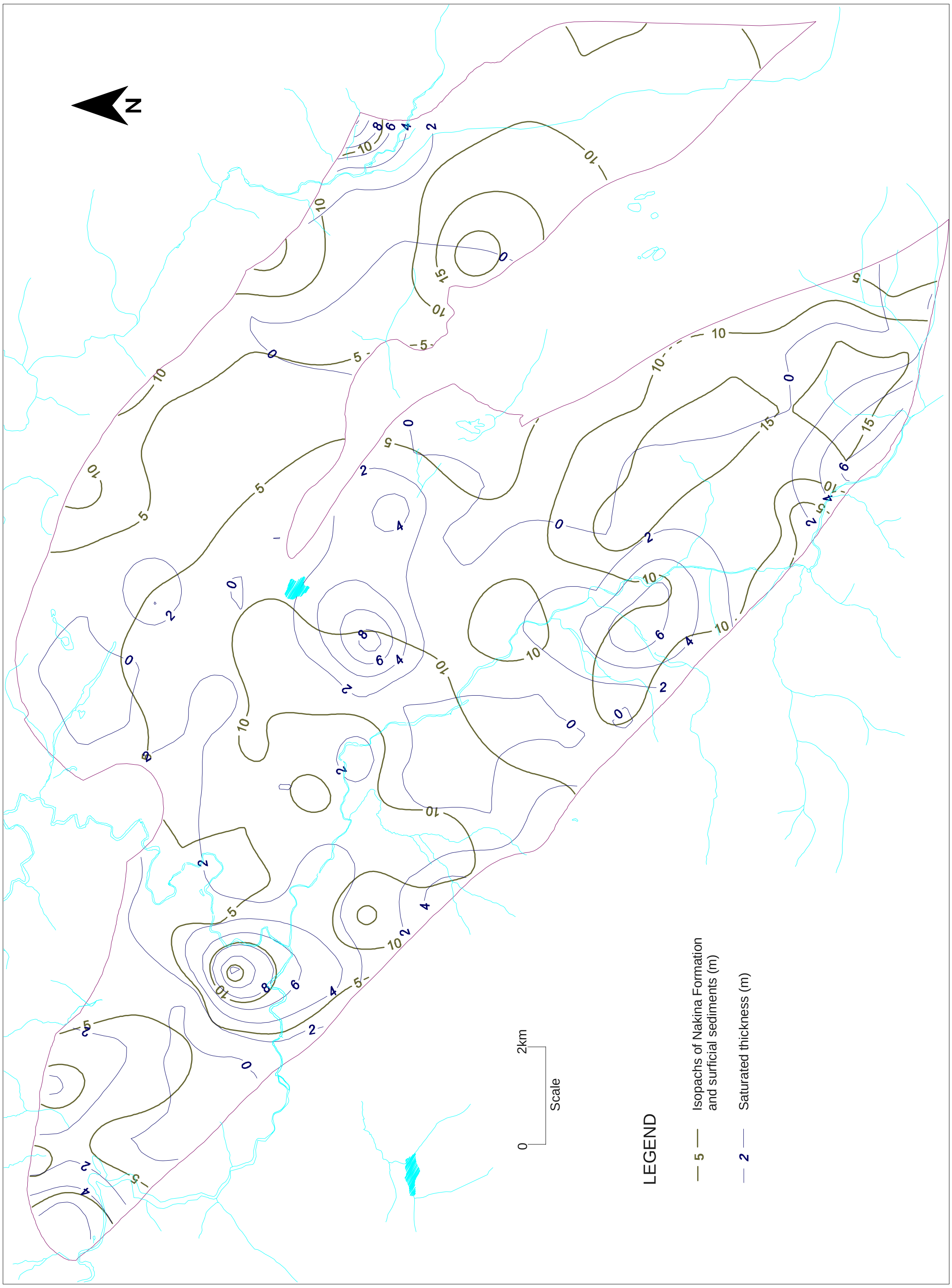


Figure 9. Nakina Formation isopachs and saturated thickness

The Muja aquifer is in direct hydraulic connection with the overlying Nakina aquifer. The Premier and Allanson aquifers are confined from above and below by extensive coal seams, except in areas of subcrop beneath the unconfined Nakina aquifer. The Ewington aquifer is confined from above by coal seams, and is underlain by the Westralia aquifer.

The Stockton aquifer is formed by the Shotts and Moorhead Formations of the Stockton Group. These sediments have been sourced in the Collie township for groundwater supplies. Groundwater is obtained mainly from the silty to very fine grained sandstones of the Stockton Group. Significant groundwater resources may be in storage within the Stockton Group; however, current information on this aquifer is limited (Brunner, 1993). The Stockton aquifer is confined from below by the granitic basement.

3.2 Groundwater flow system

A plot of watertable contours using data from both new and previously drilled shallow bores for April-May of 1998 (Fig. 10) shows that watertable elevations range from 220 m AHD near the southwestern margins of the sub-basins to 165 m AHD in the central part of the Cardiff Sub-basin and near the Collie River in the northwestern part of the basin.

Groundwater flow in the Nakina aquifer is sub-parallel to the topography. In areas where the watertable is within the Permian sediments, the local groundwater flow would be largely controlled by the stratigraphy and structure of these sediments. Faults and dipping confining beds such as coal seams and shales in the Permian sediments control groundwater flow directions. The natural groundwater flow pattern in the Collie Basin has been altered because of mine dewatering and large-scale groundwater abstraction for power generation. As a result of mine dewatering the flow is directed mainly towards the areas of mining.

In the Premier Sub-basin groundwater flows towards opencut mines, and wetlands in the low-lying areas. A groundwater mound exists in the northwestern part of the sub-basin, from where northwesterly flow discharges into the East Branch. The Stockton Ridge forms a groundwater divide between the two sub-basins in the Nakina aquifer. However, in the deeper aquifers such as the Allanson and Ewington, some groundwater flow may occur from Premier Sub-basin into the Cardiff Sub-basin.

Groundwater in the Cardiff Sub-basin flows towards the South Branch in the central part of the sub-basin where the watertable has been lowered due to dewatering of underground mines. In the southeastern corner of the sub-basin, groundwater flow is concentrated towards a localised area of low watertable in areas of subcrop of the Premier and Allanson aquifers beneath the Nakina Formation where pumping from these aquifers may have caused decline in water levels. In the northwestern part of the sub-basin, flow is to the west and groundwater discharges into the Collie River.

Flow directions in the deeper aquifers of the Collie Basin may be more obscure owing to the complex structure. Turner et al. (1999) carried out a study of groundwater residence times in the northern part of Collie Basin using CFC-12 concentrations and carbon-14 activity. The groundwater samples for the study were obtained from depths ranging from 15 m to 122 m. The results show that the samples from shallow depths contain a large proportion of ‘young’ (<50 years) groundwater, whereas the deeper samples contain 0–5% of the ‘young’ component. The age of groundwater from samples taken from deeper aquifers range from 5000 to 17 500 years, indicating a much greater residence time. The indicative groundwater flow rate based on this method was estimated as 0.5 m/year and, assuming a porosity of 0.3 and hydraulic gradient of 1:600, a corresponding hydraulic conductivity of 0.25 m/day is estimated. Therefore, very slow movement of groundwater takes place in these aquifers compared with the flow in shallow parts, which has relatively rapid replacement of groundwater.

The considerable age of groundwater in the deeper parts of the basin implies that the dipping confining beds such as coal seams, compaction of the sediments at deeper levels, and numerous faults has a significant effect on groundwater movement. For this reason, it is likely that most groundwater flux in the deeper aquifers is closer to the areas of subcrop beneath the Nakina Formation, and very slow groundwater movement takes place in the deeper parts.

As the Collie Group aquifers are confined by thick coal seams, shale and siltstone that have vertical hydraulic conductivities of the order of 10^{-5}–10^{-7} m/day, it is unlikely that any significant flow of groundwater would take place from one aquifer into another unless there are large head differences.

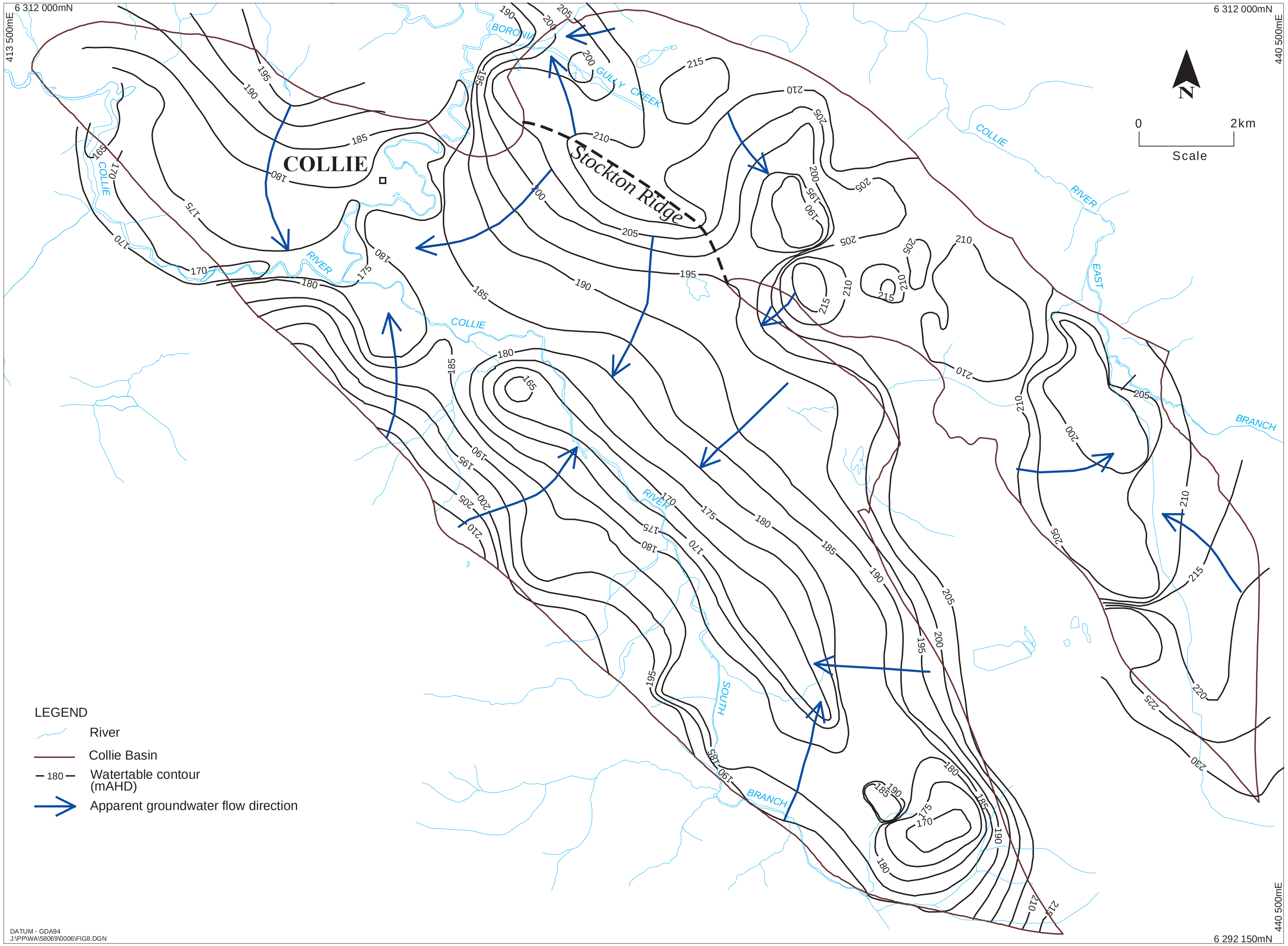


Figure 10. Watertable contours

Groundwater flow in the deeper parts of the Collie Basin has been studied using a three dimensional groundwater flow model of the basin (Varma and Zhang, 2002). For the purpose of modeling, the Muja aquifer has been separated into three model layers based on the different zones of mine dewatering – Muja 1, Muja 2 and Muja 3.The remaining model layers are similar to the corresponding hydrostratigraphic units of the basin as shown in Table 2. Groundwater flow in the deeper parts of the basin under pre-mining steady state conditions is illustrated in Figures 11 and 12. Water balances of the Collie Basin aquifers under both, pre-mining steady state and present conditions have been derived from the groundwater flow model and presented in Appendices II and III. The water balance of the aquifers of the basin shows that, under pre-mining steady-state conditions, groundwater leakage in the deeper aquifers in the Collie Basin is very low and predominantly upwards. The model shows that groundwater enters the Permian aquifers as leakage from the Nakina aquifer in the areas of subcrop, and eventually discharges back into the Nakina aquifer in areas of subcrop that underlie the Collie River. However, under present conditions, there is a significant head difference in the aquifers as result of mine dewatering; this has resulted in large volumes of leakage.

3.3 Potentiometric head distribution

Hydraulic head gradients at most of the bores, where heads from different depths are recorded, show a downward head gradient due to large-scale abstraction from deeper aquifers. The steepest downward gradient of 34 m over a 40 m interval was recorded at W677 in Western 2 underground mine area in the Cardiff Sub-basin where abstraction occurs at depths of 150–200 m. Upward head gradients were recorded in bores (ME6 and CBS5) near areas of groundwater discharge. The depth to the watertable ranges from less than 3 m in the Collie River near the northern part of the basin, to as much as 70 m in the southern part of the Cardiff Sub-basin (Fig. 13). The watertable is generally deeper in topographically high areas and shallower near valleys.

3.4 Water level fluctuation

Watertable elevation in the Collie Basin is highest in October or November and lowest in April or May. The average seasonal fluctuation of the watertable is 0.7 m with a maximum of 2.5 m. Lesser or no seasonal fluctuation is observed in bores that are near areas of previous or present groundwater abstraction. This implies that there is insignificant recharge in such areas, and/or continued water level decline due to current abstractions or downward leakage of groundwater where there is considerable vertical head gradient due to past dewatering. Higher positive fluctuations tend to be near the Collie River South Branch owing to recharge from the river.

3.5 Recharge

Groundwater recharge to the watertable is mainly via direct infiltration of rainfall. Some recharge from streams also occurs in areas where the stream bed is at a higher elevation than the watertable. Discharge of groundwater obtained from mine dewatering to Stockton Lake and South Branch provides additional recharge. Recharge to the sediments of the Collie Group takes place in areas of subcrop beneath the permeable Nakina Formation and by leakage from overlying and underlying aquifers. Groundwater recharge within the Collie Basin in the past has been estimated mainly using the chloride mass balance technique. As a part of this study, groundwater recharge has been assessed from chloride mass balance and water balance.

3.5.1 Rainfall recharge by chloride mass balance

The ratio of chloride concentration in rainfall to that in groundwater can be used to estimate the groundwater recharge by infiltration of rainfall. This method is based on the assumption that rainfall is the only source of chloride ion in the groundwater and that its concentration in the groundwater is due to evapotranspiration.

Using this technique Hirschberg (1976) estimated groundwater recharge to the basin as 3.36%. AGC (1978) estimated that groundwater recharge ranged from 5% to 18% of annual rainfall with an average of 8%. For this study, recharge from rainfall has been

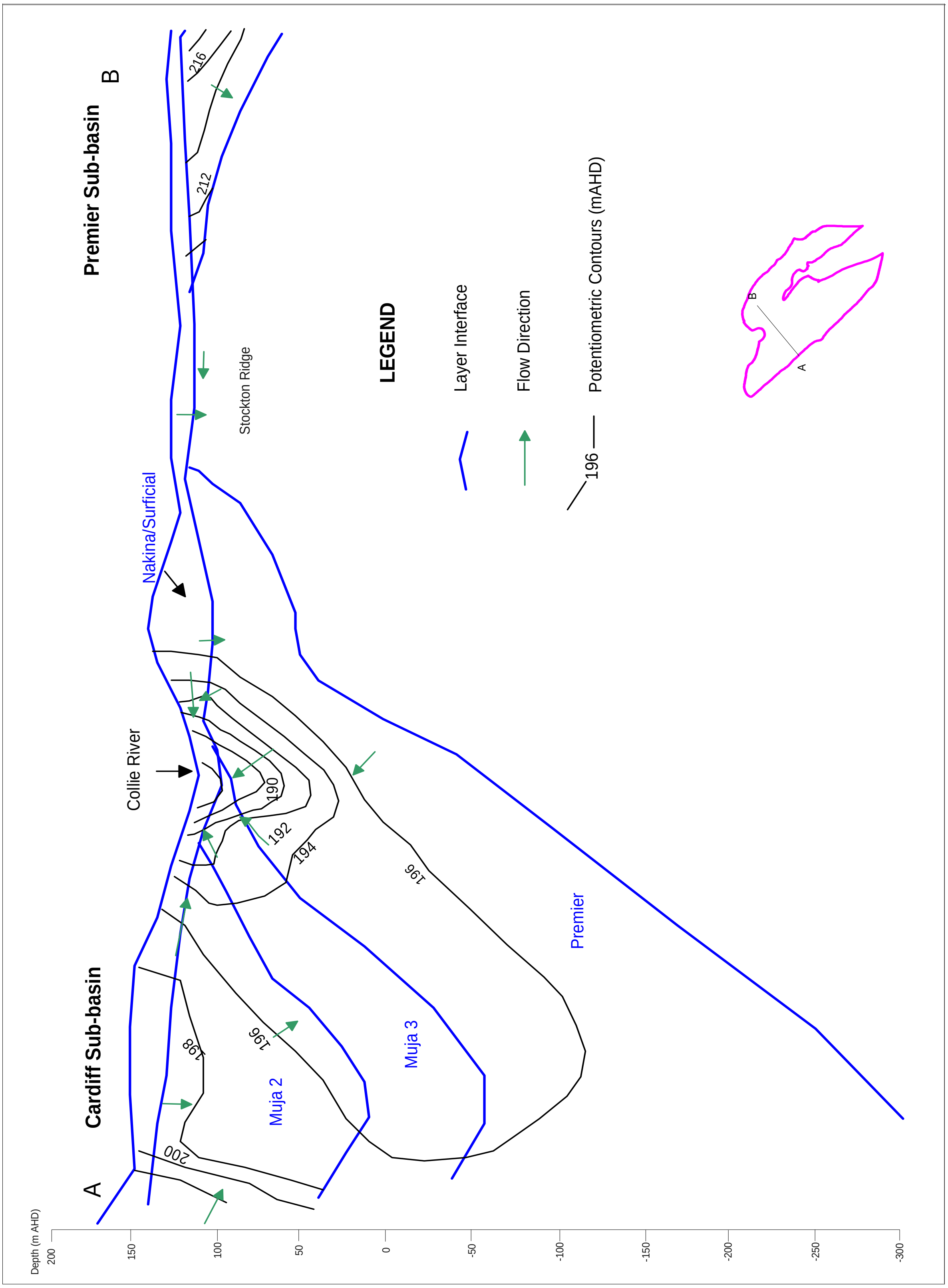


Figure 11. Schematic hydrogeological section (SW–NE)

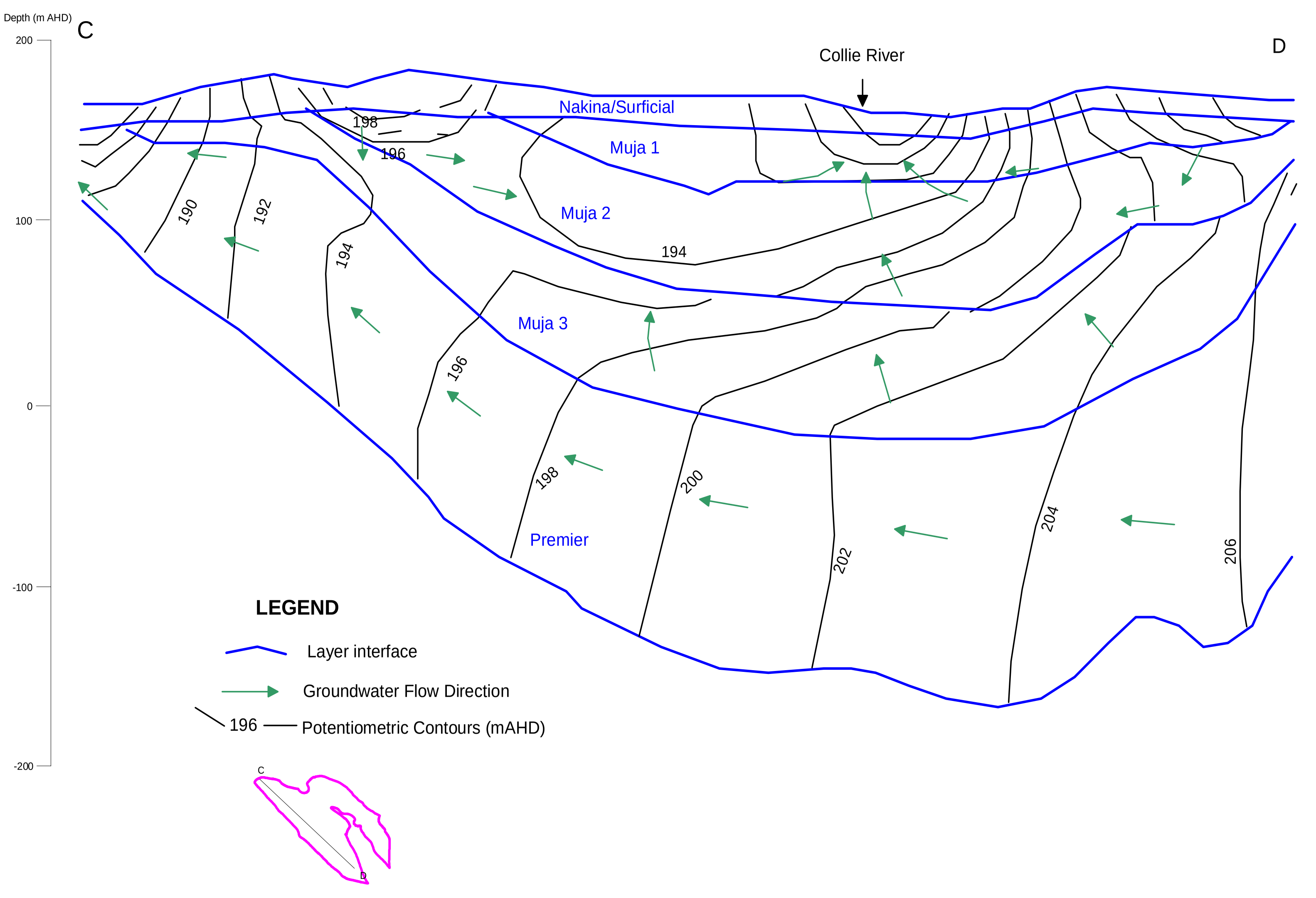


Figure 12. Schematic hydrogeological section (NW–SE)

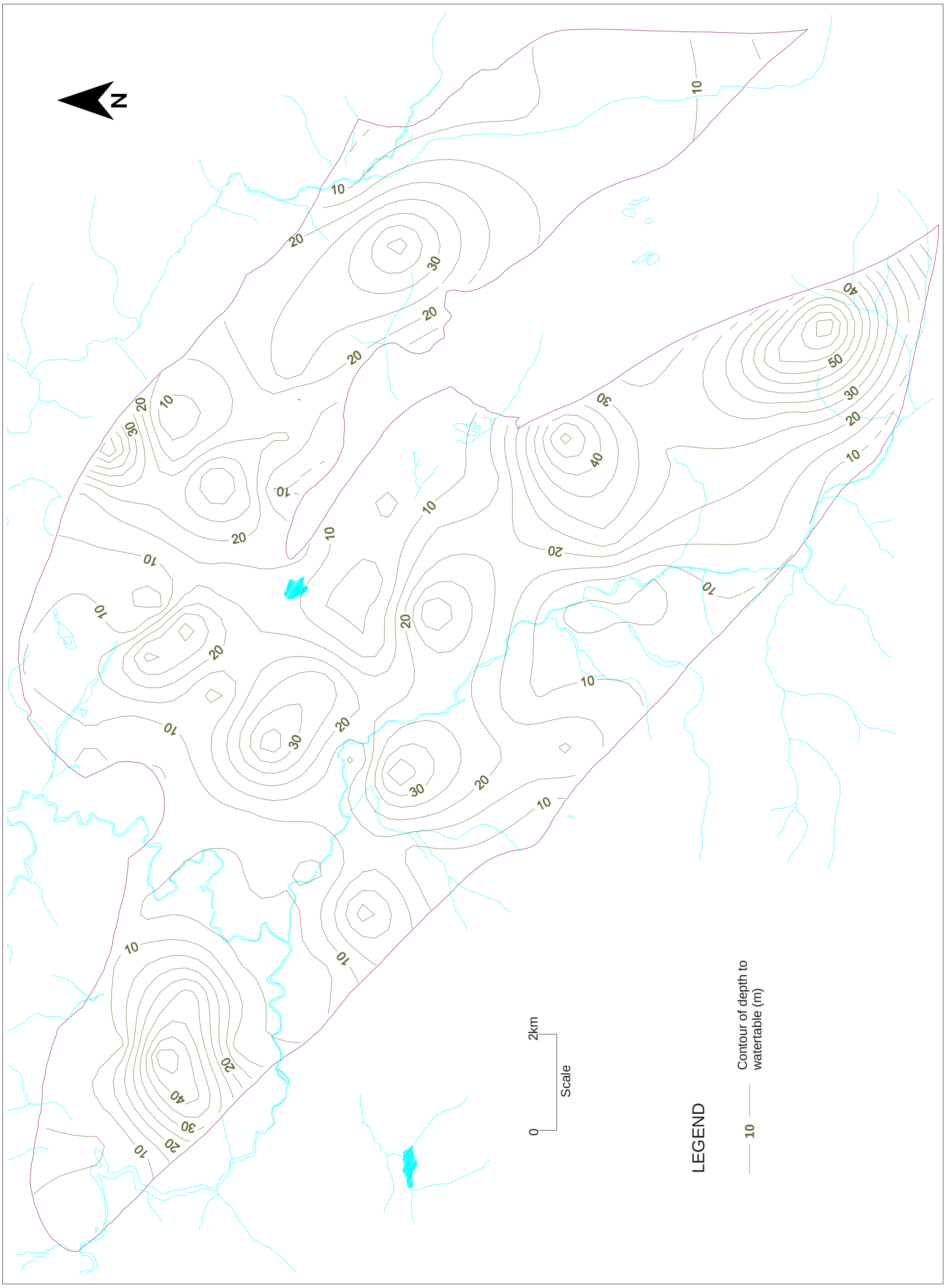


Figure 13. Depth to watertable

estimated using the distribution of chloride concentrations in groundwater at the watertable in areas where the concentration is unlikely to be affected by the recharge from brackish runoff from the Collie catchment outside the basin. Chloride concentrations in groundwater in such areas range from 30 mg/L to about 400 mg/L. Chloride concentration in rainfall at Collie is 7 mg/L (Hingston, 1990, *in* Moncrieff, 1993) in 1958. Adopting this value of chloride in the rainfall, the recharge from direct infiltration of rainfall within the basin ranges from 2% to 23% of the annual rainfall with an average of 12%. This method of recharge estimation makes several assumptions such as aquifers are silt-free, that no additional chloride is dissolved in the infiltrating rain water, and rainfall is the only source of groundwater recharge at the sampling point. In view of these assumptions, recharge from this method can only be considered a rough estimate.

3.5.2 Recharge based on groundwater balance

The establishment of groundwater balance comprises identifying, estimating and equating all components of inflow and outflow of groundwater from a system. These components have been estimated analytically based on available data and used to calculate recharge as described in detail later in this report, and summarised in Table 3.

From groundwater balance, recharge to the basin from direct infiltration of rainfall is estimated as 19 × 10^6 m^3/year, equating to 10% of annual rainfall. In addition the basin receives about 1 × 10^6 m^3/year of recharge from the South Branch and the East Branch.

Table 3. Components of groundwater balance

COMPONENT	*VOLUME (x 10^6 m^3)* *1999–2001*	 *Average per year*
INFLOW		
Rainfall recharge	38	19
Stream recharge	2	1
Total inflow (recharge)	40	20 (10%*)
OUTFLOW		
Abstraction	36	18
Groundwater discharge to river	14	7
Evaporation from vegetation	2	1
Total outflow	52	26
Change in storage (inflow-outflow)	**-12**	**-6**

* Percentage of annual rainfall

3.5.3 Recharge to Permian aquifers

The groundwater resources of the Collie Basin are mostly contained within the Permian aquifers that subcrop beneath the Nakina Formation. The Nakina Formation is unsaturated in many parts of the basin and the watertable in these areas is within the Permian sediments. Recharge to the Permian aquifers takes place from the overlying Nakina aquifer.The Collie Group aquifers are separated by shale layers and coal seams that have low hydraulic conductivities. Some leakage through these layers is, however, possible depending on hydraulic heads differences in the overlying and underlying aquifers.There is a lack of bores for monitoring water levels in deeper aquifers of the basin, and it is therefore not possible to determine the inter-aquifer leakage. Recharge to these aquifers under pre-mining steady state and present conditions have, however, been estimated using the 3D groundwater flow model of the Collie Basin, and summarised in Table 4.

Table 4. Recharge to Permian aquifers

Aquifer	*RECHARGE (x10^6 m^3/year)* Cardiff Sub-basin Pre-mining	 Present	 Premier Sub-basin Pre-mining	 Present
Muja	2.3	5.3	0.3	0.2
Premier	1.9	2.5	1.7	3.5
Allanson	2.9	3.4	0.5	0.7
Ewington	0.4	0.4	0.1	0.2
Westralia	0.3	0.3	0.1	0.1
Stockton	0.5	0.6	0	0.3
Total	**8.3**	**12.5**	**2.7**	**5.0**

The present recharge to the Permian aquifers is more than the recharge under pre-mining steady state conditions as lowering of water levels due to mine dewatering have induced additional recharge from the rivers. Also less evapotranspiration occurs as a result of lowering of the watertable. This difference in the groundwater balance would result in decreased groundwater discharge to the rivers and wetlands.

A flowchart illustrating the generalised water balance under pre-mining and present conditions, as derived from the model is given in Figures 14 and 15. A more detailed aquiferwise water balance is provided in Appendices II and III.

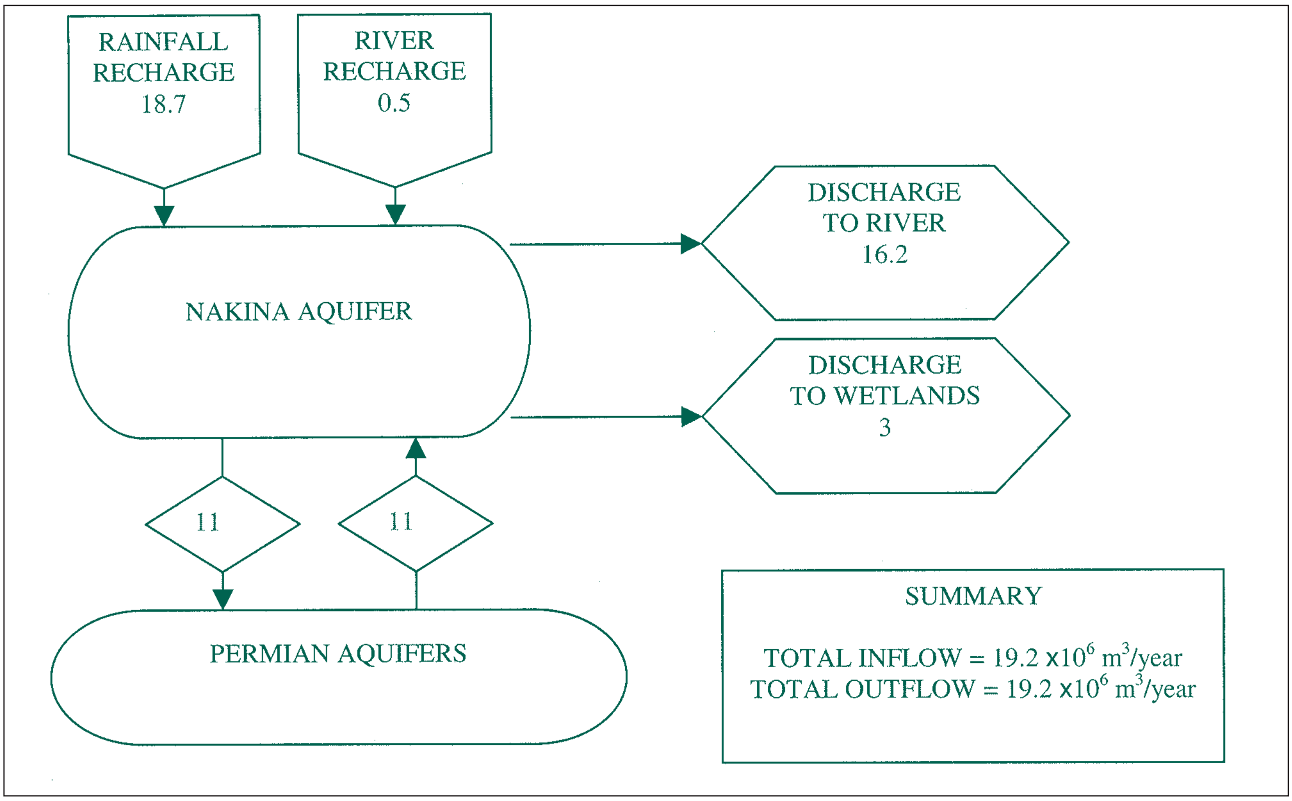


Figure 14. Generalised water balance of Collie Basin aquifers under pre-mining conditions derived from the model
(Note: All volumes are in $10^6 m^3$*)*

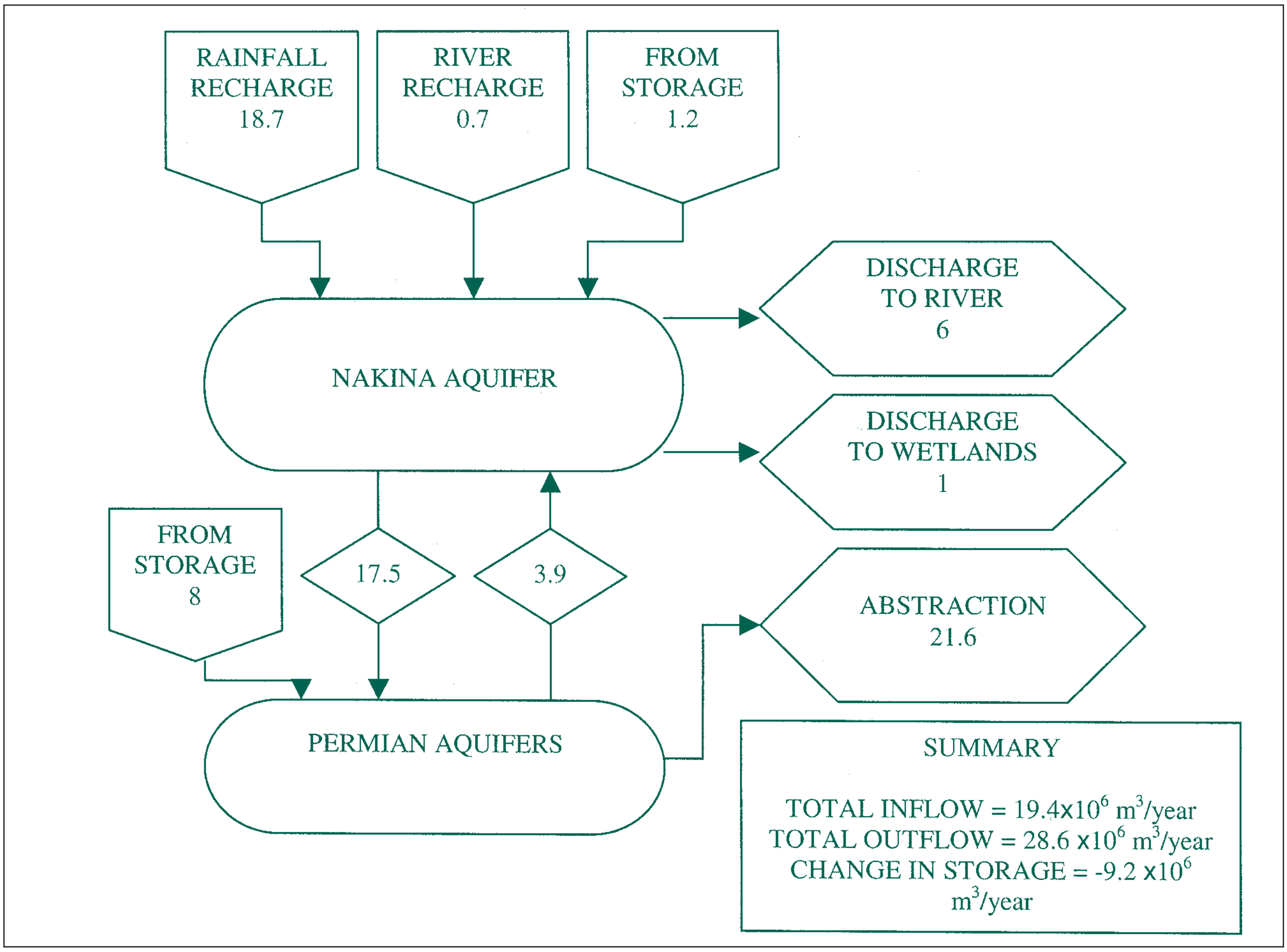


Figure 15. Generalised water balance of Collie Basin aquifers for 1999 derived from the model
(Note: All volumes are in $10^6 m^3$*)*

3.6 Groundwater discharge

Most groundwater discharge in the basin takes place by abstraction from wellfields and mine dewatering. Natural groundwater discharge from the Permian aquifers is to the overlying Nakina aquifer. Groundwater in the Nakina aquifer discharges to the Collie River and its tributaries, and by evaporation from wetlands including river pools and transpiration by vegetation that draws water directly from the watertable in areas of shallow watertable.

3.6.1 Groundwater discharge to Collie River

Groundwater discharge as baseflow to the river system in the Collie Basin takes place down-gradient of the gauging stations S612034 on South Branch and S612035 on the East Branch.The volume of groundwater discharge has been estimated as 7×10^6 m^3/year based on baseflow analysis and surface water balance as detailed in Section 5.5 of this report.

3.6.2 Evapotranspiration from vegetation

Evapotranspiration from vegetation in areas of shallow watertable is a significant component of groundwater discharge. Farrington et al. (1989) used the diurnal fluctuation method to estimate evapotranspiration from vegetation in areas where watertable is 0-3 m deep. The results showed that evapotranspiration from vegetation in such areas can be as much 110% of annual rainfall. In Collie Basin, the depth to the watertable is less than 3 m in a combined area of about 0.5×10^6 m^2. Such areas are mainly near the Collie River, South Branch and the East Branch and in some topographically depressed areas in the northern part of the Premier Sub-basin. Moncrieff (1993) measured diurnal fluctuation in the watertable in bores drilled in an area of shallow watertable, to be about 0.03 m in summer of 1990. Winter data was not collected, but according to the study of Farrington et al. (1989) diurnal fluctuation is generally not observed in winter. Adopting 0.03 m per day as the average fluctuation and 0.15 as the specific yield, the amount of groundwater uptake by vegetation in areas of shallow watertable is estimated as 1×10^6 m^3/year.

3.7 Storage

The total volume of aquifers in Collie Basin is estimated as $92\,500 \times 10^6$ m^3. It is estimated that out of this, the volume of silt-free sandstone is $71\,000 \times 10^6$ m^3. The percentage of silt-free sandstone has been interpreted from representative core logs of deep coal exploratory bores. Adopting an average specific yield of 0.1 for the sandstone in the basin, except for Nakina aquifer for which the specific yield of 0.15 is estimated, the net storage of groundwater is about 7100×10^6 m^3. The adopted specific yield values are approximate, and at depths could get as low as 0.08 (AGC, 1978) and in the shallower parts of the basin it could be as much as 0.26 (Brunner, 1993).

The estimate of storage is similar to the earlier estimates of 6750×10^6 m^3 by the Collie Land Use Working Group (1987), 7000×10^6 m^3 by Allen (1991) and 7300×10^6 m^3 by Moncrieff (1993). Estimated groundwater storage volumes for each aquifer are given in Table 5.

3.8 Aquifer parameters

The hydraulic conductivity and storage coefficient of the Collie Basin aquifers have been estimated in the past by pumping tests, granulometric analysis and slug tests by Western Collieries Limited (1991), Brunner (1993) and Henderson (1999).

As a part of this study, slug-injection and slug-recovery tests were carried out in 13 bores within the Collie Group aquifers in the areas of subcrop beneath the Nakina Formation to determine hydraulic conductivities of these aquifers. This and the aquifer parameters derived using other techniques in previous studies are given in Table 6.

The hydraulic conductivities derived from pumping tests and the granulometric analysis are generally an order higher than the values determined using slug tests. Results of pumping tests may be more accurate as the tests are performed over a longer period of time and as a result the pumping bore is more developed. The estimated storage coefficient of the Permian aquifers where they are confined are generally of the order of 10^{-3} to 10^{-4}. In the areas where the Permian strata subcrop beneath the Nakina Formation, the storage coefficient will be higher representing a semi-confined to unconfined condition.

Table 5. Groundwater storage

	Cardiff Sub-basin				*Premier Sub-basin*			
Aquifer	*Aquifer volume (x 10^6 m^3)*	*Sandstone %*	*Sandstone volume (x 10^6 m^3)*	*Aquifer storage (x 10^6 m^3)*	*Aquifer volume (x 10^6 m^3)*	*Sandstone %*	*Sandstone volume (x 10^6 m^3)*	*Aquifer storage (x 10^6 m^3)*
Nakina	450	70	315	50	50	70	35	5
Muja	6200	70	4350	435	120	70	85	9
Premier	15 200	75	11 400	1140	7000	80	5600	560
Allanson	19 500	90	17 550	1755	7500	90	6750	675
Ewington	10 500	50	5250	525	4000	60	2400	240
Westralia	9000	90	8100	810	6000	95	5700	570
Stockton	5500	40	2200	220	1500	70	1050	105
Totals	**66 350**		**49 165**	**4935**	**26 170**		**21 620**	**2164**

Table 6. Summary of aquifer parameters

Aquifer	*Pumping tests*		*Grain-size distribution*	*Slug tests*
	Hydraulic conductivity (m/day)	*Storage coefficient*	*Hydraulic conductivity (m/day)*	*Hydraulic conductivity (m/day)*
Cardiff Sub-basin				
Nakina	0.12	-	5.9	0.24
Muja	2.0	2 x 10^{-3}	-	0.12
Premier	2.3	4 x 10^{-4}	-	0.20
Allanson	5.7	4 x 10^{-4}	-	0.38
Ewington	3.2	1 x 10^{-3}	3.5	-
Westralia	-	-	-	0.002
Premier Sub-basin				
Muja	3.5	1 x 10^{-4}	2.6	0.15
Premier	4.0	3 x 10^{-4}	-	0.49
Allanson	-	-	-	0.17
Ewington	4.8	9 x 10^{-4}	-	0.04
Westralia	-	-	-	0.01

Table 7. Hydraulic parameters derived from the model

Model layer		*Zone*	*K_x (m/day)*	*K_z (m/day)*	*Zone location (m AHD)*	*Ss*	*Sy*
1	Nakina/ surficial	I	1.0	0.1	Only one zone	1e-3	0.15
2	Muja 1	I	0.6	0.006	Only one zone	5e-4	0.1
3	Muja 2	I	0.5	0.002	175 to 50	1e-6	0.1
		II	0.1	4.0e-4	50 to –50 (Not present in PSB*)	1e-6	0.1
4	Muja 3	I	0.6	1.4e-3	175 to –50	1e-6	0.1
		II	0.1	2.8e-4	50 to –200 (not present in P SB)	1e-6	0.1
5	Premier	I	0.5	2.8e-3	100 to -50 (200 to -50 in PSB)	1e-6	0.1
		II	0.1	2.8e-3	-50 to –300 (-50 to –300 in PSB)	1e-6	0.1
		III	0.02	1.1e-4	-300 to –500 (Not present in PSB)	1e-6	0.1
6	Allanson	I	2.8	0.028	200 to 0	1e-6	0.1
		II	0.5	5.0e-3	0 to –350	1e-6	0.1
		III	0.1	1.0e-3	-350 to –550	1e-6	0.1
		IV	0.02	2.0e-4	-550 to –700 (Not present in PSB)	1e-6	0.1
7	Ewington	I	0.3	0.003	200 to –500	2e-6	0.1
		II	0.06	6.0e-4	-500 to –750	2e-6	0.1
8	Westralia	I	0.2	0.002	250 to 200	1e-5	0.1
		II	0.04	4.0e-4	200 to –600	1e-5	0.1
		III	0.01	1.0e-4	-600 to –800 (Not present in PSB)	1e-5	0.1
9	Stockton	I	0.1	1.0e-3	200 to –500	1e-5	0.1
		II	0.05	5.0e-4	-500 to –1100	1e-5	0.1
10	Basement	I	0.005	0.005	Only one zone	1e-6	0.1

*Premier Sub-basin; Ss is specific storage; Sy is specific yield

There is a lack of data from the Stockton aquifer, and the Nakina aquifer in the Premier Sub-basin. Hydraulic conductivity of Allanson aquifer in Premier Sub-basin derived using groundwater flow rate of 0.5 m/year estimated by Turner et al. (1999), is about 0.25 m/d, and is similar to the hydraulic conductivity estimated from slug tests.

The general increase of hydraulic conductivities with depth/age of the aquifer in Table 6 is more related to statistical scatter of the data than a true trend. Due to the complex hydrogeology, the aquifer parameters of Collie Basin are likely to vary both laterally and vertically. The hydraulic conductivity is more likely to progressively decrease with depth due to compaction and consolidation of the sediments. Hydraulic parameters of the deeper formations encountered in deep exploratory bores could be determined by using geophysical logs, in particular, electrical and radioactive logs could be employed to obtain an understanding of the hydraulic conductivity and porosity of the deeper aquifers.

During the development of the groundwater model of the Collie Basin, the hydraulic parameters namely the horizontal and vertical hydraulic conductivities, the specific yield and storativity were calibrated. In the model, different hydraulic conductivities have been assigned to different zones within each layer depending on the depth of occurrence (Table 7). The vertical hydraulic conductivities of the Permian strata are generally about two orders less than the horizontal hydraulic conductivities.

3.9 Groundwater quality

3.9.1 Major ions

A Piper trilinear diagram based on chemical analyses of groundwater samples from Collie Basin, shows that groundwater is mainly sodium chloride type (Fig. 16).

Groundwater from a deeper bore (CBS5A) is, however, different from that of the shallow bores, and is of calcium carbonate type. Bores CBS12, CBS21A, CRM-8/98 and CRM-11/98 have higher proportion of sulfate ion. Results of chemical analyses of the CRM bores are given in Table 8.

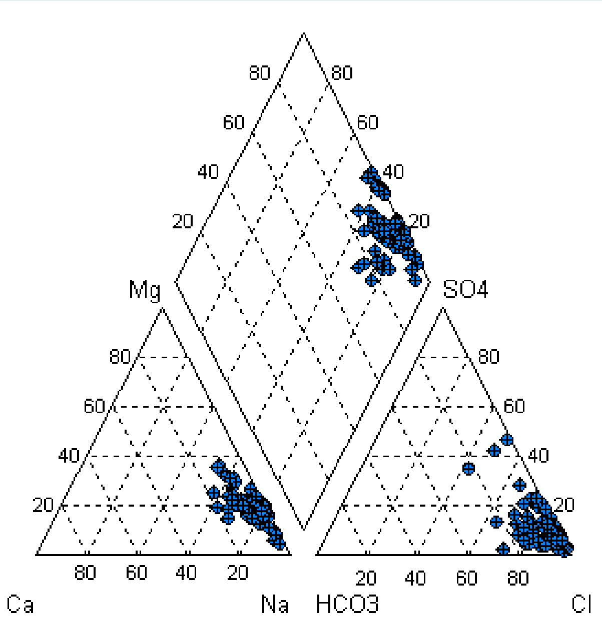


Figure 16. Groundwater quality, Piper diagram

3.9.2 pH

Groundwater in the basin is generally acidic with pH at the watertable ranging between 5 and 6 in most parts of the basin (Fig. 17). Groundwater pH is less than 5 and as low as 2.6 near the underground and open cut mines throughout the basin. The low pH of groundwater can be attributed to its contact with carbon and sulphide bearing sediments where oxidation gives rise to acidity. Groundwater from the deep production bores at Shotts and Cardiff South wellfields have pH in the range of 5 to 6.5. The groundwater in bores outside the basin has nearly neutral pH.

3.9.3 Iron

Iron concentrations in groundwater range from <0.1 mg/L to 41 mg/L. The concentration of dissolved iron depends on acidity of the groundwater, and in areas of low pH, iron concentrations are generally more than 1 mg/L and in some bores it is as high as 41 mg/L. In areas of the Collie Basin where groundwater pH is greater than 5, iron concentrations are generally less than 1 mg/L.

3.9.4 Nitrate

Nitrate at the watertable in Collie Basin is mostly less than 1 mg/L. Higher nitrate concentrations up to 11 mg/L occur in some bores near the Collie town area indicating groundwater contamination due to sources such as the septics.

3.9.5 Sulphate

Sulphate ion concentrations in Collie Basin groundwater are mostly less than 20 mg/L. Higher concentrations of up to 200 mg/L in the basin may result from oxidation of sulfides associated with coal seams and due to evaporation in areas of shallow watertable.

3.9.6 Chloride

Chloride concentrations in the Collie Basin groundwater range from 10 mg/L to as much as 2300 mg/L, but are mostly less than 500 mg/L. Higher concentrations occur mainly near water courses where groundwater is recharged from streams with brackish to saline water flows originating in the upper Collie River catchment.

3.9.7 Hardness

Hardness of water is expressed as an equivalent of calcium carbonate. Groundwater hardness in the basin generally does not exceed 100 mg/L and is commonly less than 50 mg/L. In areas where groundwater receives recharge from streams, hardness is greater. The qualitative degree or scale of hardness is subjective and would depend on source of groundwater (Davidson, 1995). For example in areas where groundwater recharge is mainly from direct infiltration of rainfall, such as Collie Basin, water may be considered hard if hardness is 100 mg/L, whereas in a coastal limestone area groundwater having a hardness of 100 mg/L may be considered as soft.

3.9.8 Heavy metals

Heavy metals were not recorded as part of this study but are known to occur in the basin particularly in the residues that are left after burning of coal (Davy and Wilson, 1989) that may be remobilised and contaminate the groundwater.

3.9.9 Salinity

Groundwater salinity in Collie Basin varies from 40 mg/L TDS in bore CRM-11/98 in the northwestern part of the basin to 4200 mg/L in bore CRM-45/98 near East Branch in the southeastern part of the basin. However, in most of the basin, the salinity is generally less than 500 mg/L (Fig. 18).

In areas closer to the South Branch in the southern part of Cardiff Sub-basin, where the river level is higher than the watertable, groundwater salinity is between 1000 mg/L and 2000 mg/L. This is due to groundwater recharge in this area from the river, which mainly contains brackish water. Outside the basin near the northern and the southeastern boundaries, the crystalline rocks and the overlying lateritic weathered profile, mainly contain brackish or saline groundwater ranging in salinity from 1000 mg/L to 17 300 mg/L. Groundwater salinity in the crystalline rocks near the western margin is less than 1000 mg/L possibly due to increased recharge from run-off from granitic outcrops, and higher rainfall.

3.9.10 Potability

Potability of groundwater in Collie Basin has not been assessed as a part of this study. National Health and Medical Research Council (NHMRC) and Agriculture and Resource Management Council of Australia and New Zealand (ARMCANZ) guidelines are used to assess the potability of water in Australia. These guidelines are continually being revised as more research data are available. The health-related and aesthetic guidelines set acceptable limits of physical, microbiological, chemical and radiological characteristics of water.

In Collie Basin, the potentially toxic pollutants associated with coal as determined by Davy and Wilson (1989) include As, Be, Cu, Mo, Ni, and U that are particularly significant in coal ash. These elements if present in groundwater can be a health concern depending on their concentrations. The low pH of groundwater is also potentially unacceptable according to aesthetic guidelines. Insufficient data exits for assessing health risks of low pH water. Groundwater salinity throughout Collie Basin is mostly within NHMRC drinking water guidelines.

The groundwater from deeper aquifers of the basin may have better quality for human consumption than the shallow aquifers. The Cardiff South wellfield that draws groundwater from depths of 100 – 400 m is presently used to supplying drinking water to Western Power facilities at Muja. Groundwater from the wellfield has pH in the range of 5-5.5, and salinity of about 350 mg/L TDS.

**Table 8. Chemical analyses of groundwater
(All units in mg/L except where mentioned otherwise)**

Bore	*Total . Hard*	*Total Alk.*	*TDS*	*Col. (CU)*	*pH*	*EC (mS/cm)*	*Fe*	*P*	*Na*	*K*	*Ca*	*Mg*	*Mn*	*Cl*	*SO_4*	*NO_3*	*CO_3*	*HCO_3*	*F*	*B*
CRM-01	39	14	130	1.8	5.7	280	<0.1	0.130	30	2	8	5	0.110	70	12	<1	<1	14	<0.2	0.043
CRM-03	1100	37	3480	2	5.7	5600	0.2	0.030	680	12	100	210	1.600	1700	52	<1	<1	37	<0.2	0.025
CRM-04	88	2	630	6	4.7	1150	28	<0.005	160	4	6	18	0.240	290	41	2	<1	2	<0.2	0.025
CRM-05	98	<1	820	3	3.9	1700	1.9	0.046	230	1	<1	24	0.091	440	60	<1	<1	<1	<0.2	0.021
CRM-06	120	10	660	4.3	5.4	1280	0.9	0.010	170	7	5	27	0.570	350	21	1	<1	10	<0.2	0.044
CRM-07	830	50	6080	3	5.6	11000	0.4	0.019	1900	25	58	170	1.100	3200	240	2	<1	50	<0.2	0.086
CRM-08	22	4	330	2	4.9	590	0.7	0.015	90	9	3	3	0.510	90	110	1	<1	4	<0.2	0.020
CRM-09	280	3	1610	2	4.7	3000	0.2	<0.005	450	2	4	66	0.012	900	48	8	<1	3	<0.2	0.013
CRM-10	83	50	420	35	5.2	850	6.9	0.007	110	2	5	17	0.210	220	26	<1	<1	<1	0.2	0.180
CRM-11	7	9	40	6	5.3	110	<0.1	0.140	10	2	1	1	0.190	10	11	<1	<1	9	<0.2	0.014
CRM-12	89	2	580	6.8	4.8	1100	<0.1	0.039	160	4	4	19	0.016	310	39	7	<1	2	<0.2	0.027
CRM-13	18	12	100	11	5.5	210	0.9	0.060	30	1	1	4	0.091	40	5	<1	<1	12	<0.2	0.016
CRM-15	52	4	360	1.8	4.8	750	<0.1	0.026	110	7	3	11	0.008	200	14	<1	<1	4	<0.2	0.028
CRM-17	49	33	220	51	5.9	400	2.8	<0.005	40	13	5	9	0.330	100	7	<1	<1	33	0.2	0.220
CRM-18	15	11	70	26	5.3	170	0.4	0.006	20	<1	2	3	0.011	30	7	<1	<1	11	0.2	0.150
CRM-19	58	18	380	3	5.6	730	3.6	<0.005	110	1	7	10	0.110	180	22	<1	<1	18	0.2	0.098
CRM-20	52	<1	300	5.5	4.1	630	0.2	<0.005	80	2	3	11	0.022	140	32	6	<1	<1	<0.2	0.033
CRM-21	35	6	230	11	4.9	450	0.4	<0.005	60	6	2	7	0.029	120	9	<1	<1	6	0.2	0.200
CRM-22	33	12	180	4.3	5.2	390	0.3	0.035	60	1	4	6	0.020	100	7	<1	<1	12	0.2	0.025
CRM-23	23	9	70	5.5	5.5	200	<0.1	0.021	20	6	4	3	0.110	40	7	5	<1	9	<0.2	0.025
CRM-24	45	7	240	2	5.3	520	1.9	0.017	60	5	6	7	1.500	130	15	<1	<1	7	<0.2	0.037
CRM-25	42	<1	300	1.6	4.3	460	0.2	<0.005	80	6	4	8	0.045	160	12	1	<1	<1	0.2	0.180
CRM-27	30	30	130	3	6.6	270	1.1	0.062	30	14	4	5	0.200	50	2	11	<1	30	<0.2	0.023
CRM-28	52	21	230	3	6	460	1.2	0.280	60	3	6	9	0.380	100	28	<1	<1	21	<0.2	0.022
CRM-30	18	<1	230	4	4.4	460	3.1	<0.005	70	<1	1	4	0.012	100	36	1	<1	<1	0.2	0.019
CRM-31	350	<1	2100	4.3	3.8	4300	0.1	0.031	640	3	2	85	0.054	1300	130	<1	<1	<1	0.2	0.017
CRM-32	16	5	170	<1	5.4	240	1.5	0.370	30	2	2	3	0.058	50	21	<1	<1	5	0.2	0.040
CRM-33	48	16	180	1.8	6	380	4.5	0.010	40	4	6	8	0.220	50	59	1	<1	16	<0.2	0.027
CRM-34	100	10	580	3	5.2	1120	0.3	<0.005	160	6	6	22	0.420	290	24	<1	<1	10	<0.2	0.024
CRM-35	34	13	150	4	5.4	270	0.3	0.011	40	2	1	8	0.270	60	9	<1	<1	13	0.2	0.018
CRM-37	63	32	410	1.6	6.3	770	8	<0.005	90	21	5	12	0.550	200	<5	<1	<1	32	0.3	0.170
CRM-38	26	6	140	5.5	5.5	330	1.5	0.010	40	1	2	5	0.077	70	12	<1	<1	6	<0.2	0.037
CRM-39	22	6	160	12	5.1	310	4	<0.005	40	5	2	4	0.740	70	13	<1	<1	6	0.3	0.140
CRM-40	17	7	150	1.6	5.2	320	3.1	<0.005	60	1	1	3	0.064	70	13	<1	<1	7	0.2	0.017
CRM-41	45	22	210	<1	5.6	430	0.3	0.007	50	10	6	8	0.210	110	7	1	<1	22	<0.2	0.016
CRM-42	51	9	400	2	5.3	750	<0.1	0.130	100	11	6	11	0.820	110	16	<1	<1	41	<0.2	0.014
CRM-43	49	9	290	11	5	580	41	<0.005	90	2	4	9	0.140	150	16	<1	<1	9	0.2	0.024
CRM-44	26	23	160	4	5.5	320	0.1	5.900	40	8	2	5	0.290	80	6	<1	<1	23	<0.2	0.010
CRM-45	1400	63	4200	2	6.3	7100	5.2	<0.005	920	12	120	260	0.870	2300	51	<1	<1	63	<0.2	0.024

Table 8. Chemical analyses of groundwater *(Continued)*

Bore	*Total . Hard*	*Total Alk.*	*TDS*	*Col. (CU)*	*pH*	*EC (mS/cm)*	*Fe*	*P*	*Na*	*K*	*Ca*	*Mg*	*Mn*	*Cl*	SO_4	NO_3	CO_3	HCO_3	*F*	*B*
CRM-46	5000	<1	17300	4	4	25000	3.2	0.021	3700	19	360	990	1.400	9000	330	<1	<1	<1	1.5	0.017
CRM-47	37	10	260	8	5.4	530	<0.1	0.290	60	21	2	8	0.140	140	7	1	<1	10	<0.2	0.025
CRM-48	68	16	370	2	5.5	660	0.3	0.020	80	16	6	13	0.190	160	10	3	<1	16	0.2	0.015
CRM-50	120	1	660	6	5.2	1200	3.8	0.013	170	6	5	26	0.100	330	19	<1	<1	1	0.2	0.007
CRM-51	51	41	240	4	5.9	510	<0.1	0.660	70	4	4	10	0.960	110	16	<1	<1	41	<0.2	0.008
CRM-52	60	21	260	9.6	5.5	480	8	0.006	60	7	13	7	1.300	110	24	<1	<1	21	0.2	0.220
CRM-53	12	2	80	1.6	4.8	170	2	<0.005	30	1	1	2	0.020	30	10	<1	<1	2	0.2	0.200
CRM-54	49	<1	390	2	4.2	780	<0.1	0.005	110	2	1	11	0.006	190	12	<1	<1	<1	0.2	0.015
CRM-55	22	10	130	3	5.5	260	0.1	0.016	30	4	2	4	0.026	60	5	3	<1	10	<0.2	0.006
CRM-56	260	22	1270	2	5.7	2600	6.3	0.030	350	4	8	59	0.200	680	120	<1	<1	22	<0.2	0.005
CRM-58	740	40	4720	<1	5.6	8500	0.4	0.020	1500	10	94	120	2.500	2600	180	<1	<1	40	<0.2	0.032
CRM-59	300	150	970	6.8	6.5	1870	0.8	0.140	240	12	42	48	0.670	440	47	<1	<1	150	0.2	0.033
CRM-60	22	7	130	6.8	5	280	0.1	0.160	30	7	2	4	0.055	60	5	6	<1	7	<0.2	0.017
CRM-61	450	<1	1620	27	4.2	2800	5.1	0.052	350	17	34	88	0.760	720	170	<1	<1	<1	0.2	0.015
CRM-62	68	12	370	7	5.8	730	<0.1	0.400	110	8	4	14	0.240	190	7	1	<1	12	<0.2	0.009
CRM-63	56	<1	380	15	4.5	690	2.2	0.050	100	2	3	12	0.073	160	29	<1	<1	<1	0.2	0.026
CRM-65	170	5	1020	<1	4.9	2010	<0.1	0.013	340	4	6	38	0.024	550	66	2	<1	20	<0.2	0.030
CRM-66	120	12	600	4	5.3	1100	1.3	0.020	160	5	8	25	0.510	280	17	<1	<1	12	0.2	0.010
CRM-67	72	18	470	14	5.5	850	0.6	0.020	130	15	4	15	0.460	210	22	<1	<1	18	0.2	0.011
CRM-68	440	<1	1680	3	3.9	2800	22	0.087	360	15	32	87	2.600	640	200	<1	<1	<1	0.2	0.007
CRM-69	33	4	190	4.3	5.2	450	<0.1	0.029	60	3	4	6	0.086	110	11	5	<1	4	<0.2	0.026
CRM-70	64	21	300	2	5.7	650	0.2	0.015	90	6	8	11	0.100	160	12	<1	<1	21	<0.2	0.026
CRM-71	460	12	1170	3	6.2	2000	0.5	<0.005	250	18	38	89	1.400	520	72	<1	<1	12	0.2	0.022
CRM-72	28	24	140	<1	5.4	240	<0.1	2.400	30	2	3	5	0.370	40	11	5	<1	24	<0.2	0.024
CRM-73	78	20	370	3	5.5	640	0.2	<0.005	80	4	11	12	0.230	160	13	<1	<1	20	<0.2	0.024
CRM-74	33	9	210	2	5.4	440	3.9	0.054	50	12	2	7	0.470	120	8	<1	<1	9	<0.2	<0.005
CRM-75	15	12	110	6	5.9	210	<0.1	0.050	30	2	1	3	0.012	40	8	<1	<1	12	<0.2	<0.005
CRM-76	47	20	160	6	6.1	310	<0.1	0.110	30	7	8	7	0.690	60	19	5	<1	20	<0.2	0.007
CRM-77	900	78	2390	2	6.2	4300	2.8	0.005	490	14	86	170	5.900	1200	82	<1	<1	78	<0.2	0.023
CRM-78	37	11	220	23	5.5	440	<0.1	<0.005	60	2	5	6	0.220	120	27	<0.01	<1	11	<0.2	0.017
CRM-79	270	<1	1760	6	4.1	3200	0.6	<0.005	470	10	5	63	0.260	860	72	<1	<1	<1	0.2	0.008
CRM-80	360	17	1240	2	5.7	2100	<0.1	0.070	260	21	29	70	0.170	480	200	4	<1	17	0.2	0.013
CRM-82	110	40	480	6	6.2	830	<0.1	0.096	100	12	16	18	0.130	200	16	4	<1	40	<0.2	0.032
CRM-83	40	3	240	7	4.8	490	<0.1	0.390	70	7	2	9	0.036	130	15	<1	<1	3	<0.2	0.005
CRM-84	40	7	250	2	5.2	500	<0.1	0.130	70	15	2	9	0.088	130	11	4	<1	7	<0.2	0.008
CRM-85	18	19	420	20	5.6	690	0.1	0.050	110	2	2	3	0.180	130	75	<1	<1	19	0.2	0.110
CRM-86	92	<1	560	9	4.5	1130	<0.1	0.170	170	2	4	20	0.091	310	27	<1	<1	<1	<0.2	0.009
CRM-87	160	50	740	4.3	6.3	1300	0.6	0.054	190	10	20	28	1.600	330	17	2	<1	50	<0.2	0.031
CRM-89	97	17	640	2	5.6	1210	3.9	0.036	180	18	5	21	0.320	290	59	<1	<1	17	<0.2	0.009
CRM-90	170	50	700	26	6.2	1140	0.8	<0.005	150	12	24	27	0.390	250	97	<0.01	<1	50	<0.2	0.023

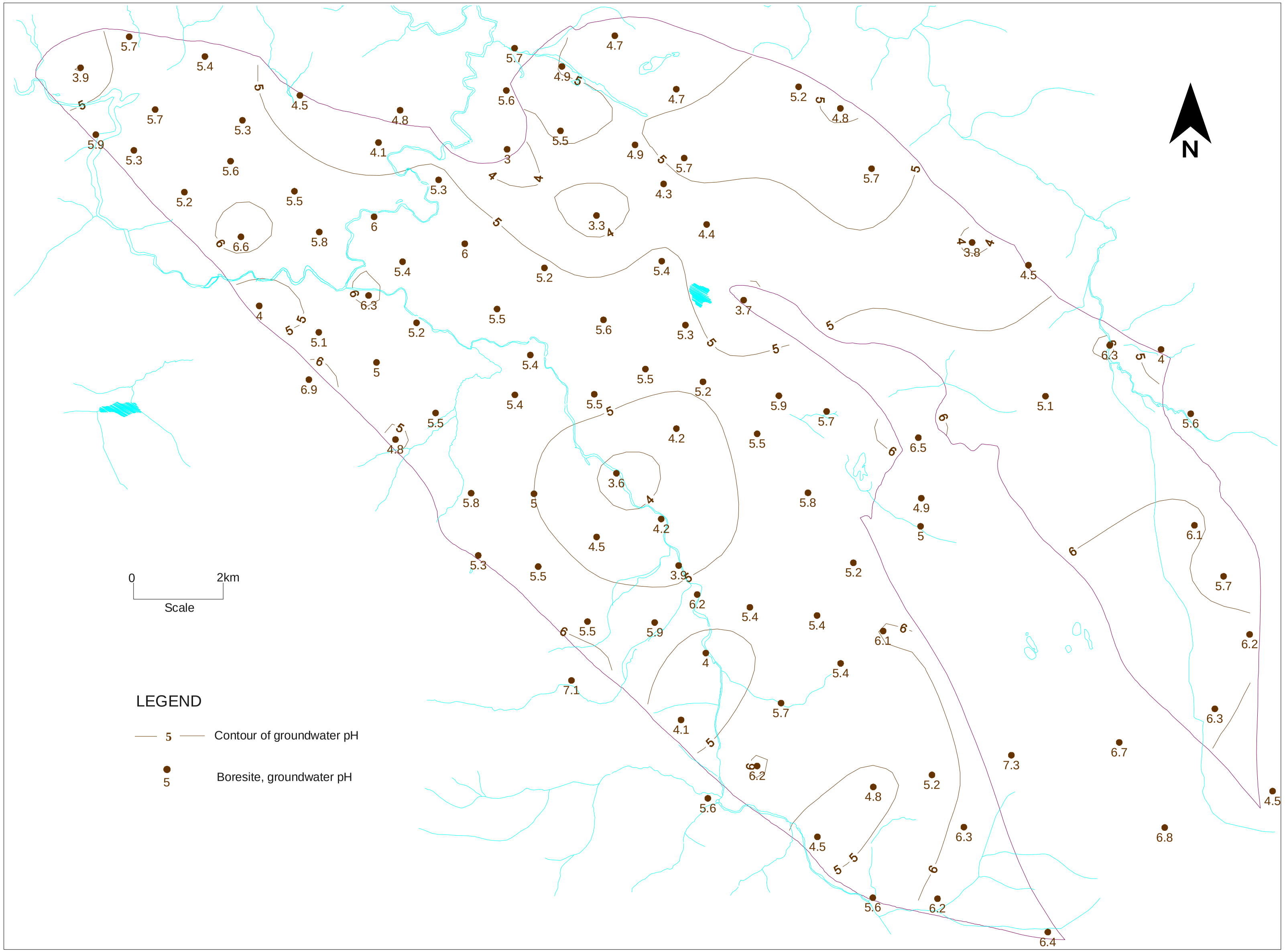


Figure 17. Groundwater pH

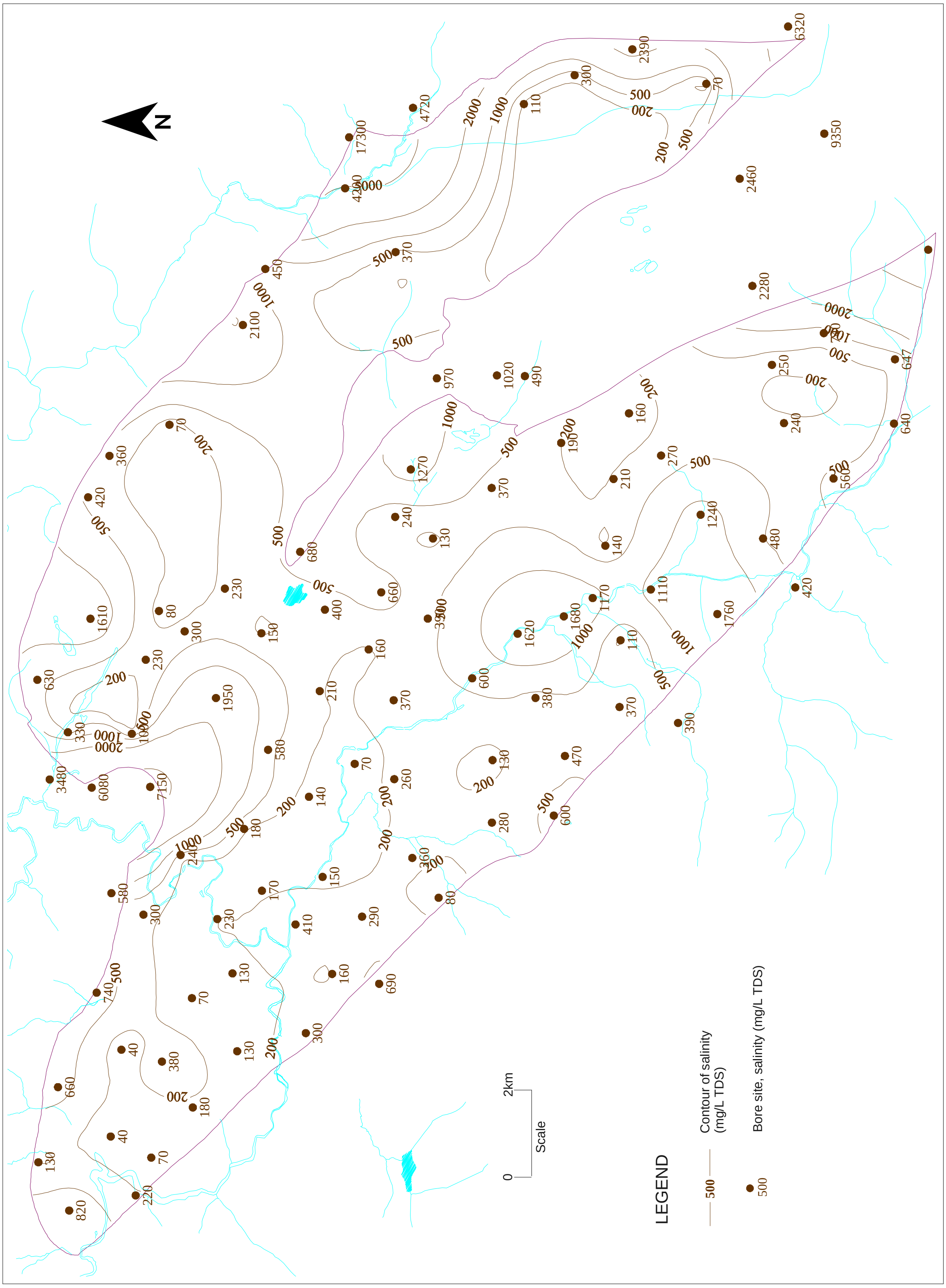


Figure 18. Groundwater salinity at watertable

4 Groundwater abstraction and impacts

4.1 Historical groundwater abstraction

Coal mining in the Collie Basin has taken place since 1898. As the coal mines in the basin extend below the watertable, dewatering and depressurisation of the aquifers have been necessary to control inflows to the mines. Since the 1960s, most of the groundwater from the mines has been diverted to the Muja and Collie Power Stations. Groundwater has also been abstracted for domestic and stock water supplies. In recent years, groundwater has been used to meet some environmental water requirements by maintaining river flows in summer. A summary of recent groundwater abstractions (since 1984) is given in Table 9. In 1994, all underground mining in Collie Basin ended, resulting in a major reduction in mine dewatering in the Cardiff Sub-basin. In 1997, there was further reduction in mine dewatering due to closure of the Western 5 opencut mines. Abstraction from some underground mines, however, continued after 1994, to supply groundwater to the power stations. Since 1995, mine dewatering in the Premier Sub-basin increased after commencement of mining at the Premier opencut mines. From 1998, there was further reduction in the power station use of groundwater as a result of CWAG strategies for minimising groundwater abstraction in the basin to enhance recovery of water levels.

Although coal mining, and hence dewatering, has taken place in the Collie Basin since 1898, records of groundwater abstraction are available only since 1984. An estimate of past mine dewatering volumes has, however, been obtained by correlating past coal production with known mine dewatering data.

Figure 19 shows a good correlation between coal production and mine dewatering in the Collie Basin between 1984 and 1996. This correlation is achieved when a time lag of two years is set between the

Table 9. Summary of recent groundwater abstraction

Wellfield/ mine	*Period of operation*	*Aquifer(s) intersected*	*Average groundwater abstraction (x 10^6 m^3/year)*			*Comments*
			1984-1994	**1995-1997**	**1998-2000**	
CARDIFF SUB-BASIN						
Western 2 u/g* mine	1952 to present	Muja	6.11	3.29	2.28	Only power station supply after 1994
Western 5 o/c[#] mine	1970–1997	Muja	2.12	1.05	-	Mining ceased in 1997
Western 5H o/c	1987–1996	Ewington	0.75	0.66	-	
Western 6 u/g mine	1982 to present	Muja	3.81	1.67	1.23	Only power station supply after 1994
Western 7 u/g	1984–1994	Muja	2.61	-	-	
Cardiff South wellfield	1985 to present	Premier, Allan-son, Ewington, Westralia	2.72	3.22	3.23	Commissioned in 1985
Sub-total (Cardiff Sub-basin)			**18.12**	**9.89**	**6.74**	
PREMIER SUB-BASIN						
Muja o/c mine	1953 to present	Muja, Premier	4.20	2.76	3.57	All groundwater diverted for power station supply
Chicken ck o/c mine	1981–1997	Premier	1.83	1.78	0.30	
Ewington II o/c mine	1996 to present	Premier	-	1.91	2.70	
Premier o/c mine	1995 to present	Premier	-	2.03	2.03	
Shotts wellfield	1981 to present	Premier, Allanson	2.82	3.00	2.28	Commissioned in 1981
Sub-total (Premier Sub-basin)			**8.85**	**11.48**	**10.88**	
TOTAL (COLLIE BASIN)			**26.97**	**21.37**	**17.62**	

*u/g: underground; [#]o/c: opencut

dewatering and the coal production. Since 1996, most coal has been produced in the Premier Sub-basin where areas around mines have been dewatered in the past to an extent that mining can operate with relatively much less dewatering. Applying the relationship from Figure 19 to past coal production data in the basin, mine dewatering for the period from 1900 to 1984 has been estimated as shown in Figure 20.

Coal mining and hence mine dewatering in the Collie Basin has been increasing with time. There was a sharp rise in coal production, and hence mine dewatering in the basin, after 1970 with the commencement of opencut mining at Western 5 in the Muja Coal Measures in the Cardiff Sub-basin.

Figure 21 shows a good correlation between mine dewatering and coal production from the Muja Coal Measures in the Cardiff Sub-basin between 1984 and 2000. The best correlation is achieved by setting a time lag of 2 years between mine dewatering and subsequent coal production.

Applying the mathematical relationship derived from this correlation, past mine dewatering has been interpreted as shown in Figure 22.

In the Cardiff Sub-basin, an average of about 14.6×10^6 m^3/year of groundwater has been abstracted between 1984 and 1994 from the Muja aquifer, which under pre-mining steady-state conditions, received an estimated groundwater recharge of 2.6×10^6 m^3/year. Figure 22 shows that groundwater abstraction from the Muja aquifer has been increasing since early 1900 when mining at Cardiff–Neath, and later Wyvern, Phoenix and Western 5 opencut commenced. Groundwater abstraction continued to increase with commencement of mining at Western 2 in 1952, and then Western 5, 6 and 7 mines in the 1970s and 1980s. Mining, and hence dewatering, reached a maximum in 1992. The graph shows that abstraction from the Muja Coal Measures would have exceeded recharge after the 1950s following commencement of mining at Western 2 underground mine. However, dewatering and lowering of water levels would have induced additional recharge to the Muja Coal Measures from the Collie River South Branch and the underlying strata.

Abstraction declined to an average of 5.4×10^6 m^3/year after cessation of underground mining at Western 2, 6 and 7 in 1994, and declined further to a average of 3.5×10^6 m^3/year after completion of opencut mining at Western 5 in 1997. However, abstraction from the abandoned Western 2 and Western 6 mines continued beyond 1994 for power station supply.

After setting a two year lag between the dewatering and the coal production, a good correlation also exists between mine dewatering and coal production in the Premier Sub-basin for data since 1984, (Figure 23).

Applying the mathematical relationship derived from this correlation, the interpreted pre-1984 mine dewatering in the Premier Sub-basin is as shown in Figure 24.

Interpreted historical groundwater abstraction from mines in the Premier Sub-basin shows a continuous increase since the 1950s after commencement of mining at Hebe underground and Muja opencut mines. Dewatering increased sharply in the 1990s with mining at the Premier mine pits. Recharge to the Premier Sub-basin is estimated as 2.7×10^6 m^3/year under pre-mining steady-state conditions. Dewatering from the Premier Sub-basin was less than recharge until the 1980s, after which mining of groundwater would have occurred due to increased mine dewatering. The average groundwater abstraction and dewatering was about 9×10^6 m^3/year during 1984–1994, and this increased to 11.5×10^6 m^3/year after 1995, which is about four times the estimated recharge to the sub-basin.

4.2 Groundwater levels recovery/ decline

Hydrographs of watertable monitoring bores have been analysed to assess the changes in water levels in the Collie Basin with respect to abstraction.

Owing to abstractions exceeding the recharge, plots of end of summer water levels at selected boresites in the Muja aquifer in the Cardiff Sub-basin (Fig. 25) show a decline until 1994.

Since 1995, abstraction from the Muja aquifer has been within current recharge and hence shallow groundwater levels have been recovering at rates of 0.2–0.5 m/year. Watertable elevations in the Muja aquifer, however, do not represent the actual change in storage as downward leakage continues to occur in the deeper parts that have been dewatered for mining.

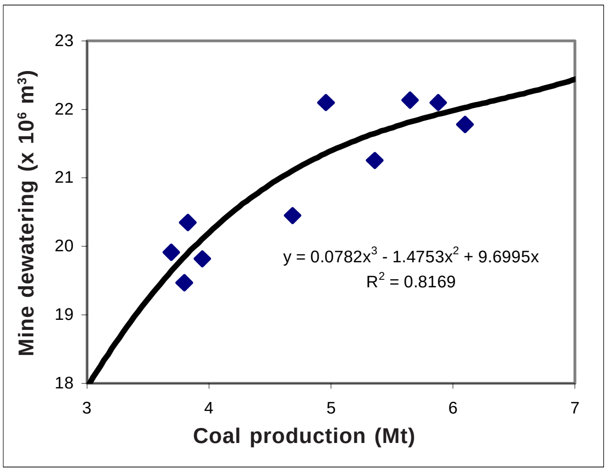


Figure 19. Correlation between coal production and mine dewatering in the Collie Basin

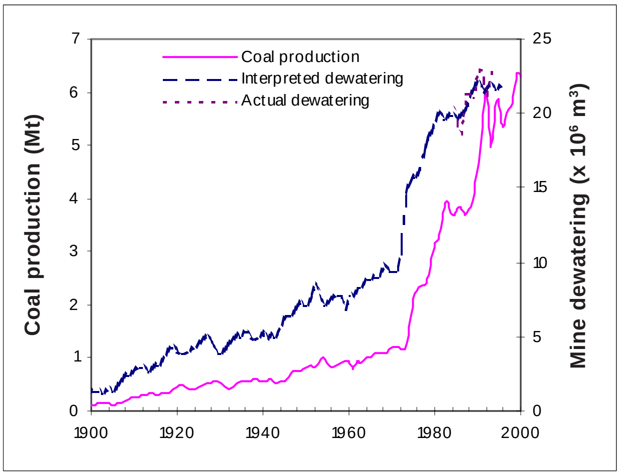


Figure 20. Interpreted past mine dewatering from the Collie Basin

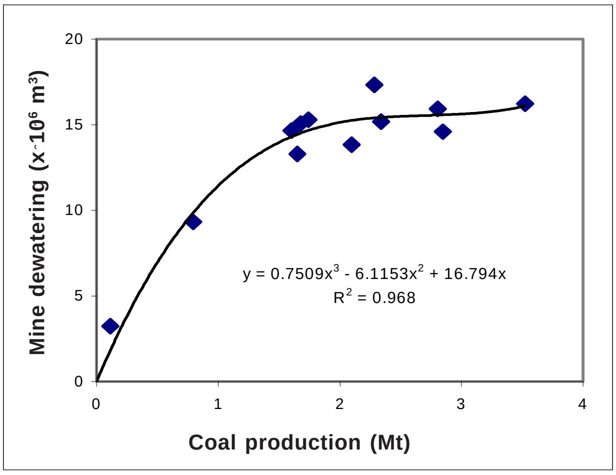


Figure 21. Correlation between coal production and mine dewatering in the Muja Coal Measures (Cardiff Sub-basin)

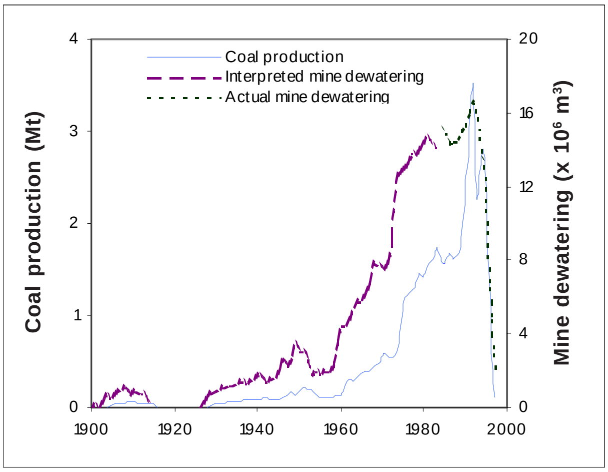


Figure 22. Interpreted past mine dewatering from the Muja Coal Measures (Cardiff Sub-basin)

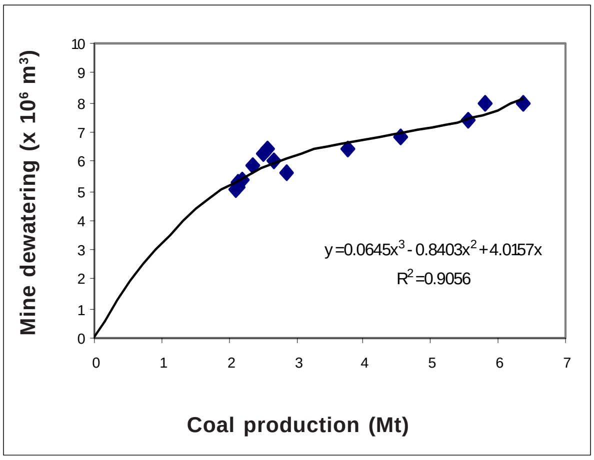


Figure 23. Correlation between coal production and mine dewatering in the Premier Sub-basin

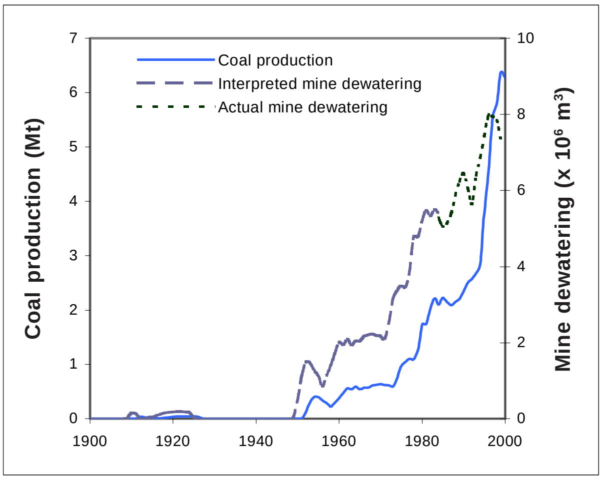


Figure 24. Interpreted past mine dewatering from the Premier Sub-basin

Most abstraction from the Premier, Allanson and Ewington aquifers of the Cardiff Sub-basin has taken place since 1985 from Cardiff South wellfield at an average rate of 2.7–3.2 × 10^6 m^3/year (Table 9). Although abstraction has always been within the recharge limits (5.5 × 10^6 m^3/year), water levels in these aquifers near the Cardiff South wellfield declined between 1998 and 2000 at 0.5–1.0 m/year (Fig. 26). The reasons for this decline could be

- Truncation of the aquifers due to faulting and hence decreased recharge,
- The wellfield has not attained steady state condition, or
- There is leakage from these aquifers to the Muja aquifer where heads are lowered due to large-scale dewatering in the past.

Groundwater modeling has shown that in response to reduced heads in Muja aquifer, there is significant flow of groundwater from the Premier aquifer to the overlying Muja aquifer under present conditions (2.7 × 10^6 m^3/year) compared with pre-mining steady-state conditions (0.3 × 10^6 m^3/year).

In the Premier Sub-basin, groundwater abstraction occurs mainly from the Premier, Allanson and Muja aquifers. Abstraction from the Allanson aquifer took place in the Shotts wellfield between 1984 and 1997. It is estimated that an average of 1.5 × 10^6 m^3/year was abstracted from the Allanson aquifer from the Shotts wellfield. Bores CBS14A and CBS32 that monitor water levels in the area beneath which this aquifer subcrops have not shown any significant decline in the water levels (Fig. 27), indicating that abstraction from this aquifer has occurred within recharge.

Abstraction from the Premier aquifer, from the Shotts wellfield and the opencut mines, in the Premier Sub-basin has been significantly higher than the estimated recharge of 1.7 × 10^6 m^3/year. As a result, water levels in bores CBS21D and CBS29 that are installed in this aquifer have declined at the rate of 1 to 2.5 m/year. The rainfall during the period of assessment (1984–2000) has remained stable. This implies that decline in water level is due mainly to abstractions and not climatic factors. While there has been about 20% decline in the average annual rainfall in the Collie Basin, as in the entire southwest of Western Australia since 1950, increased mining and consequent clearing

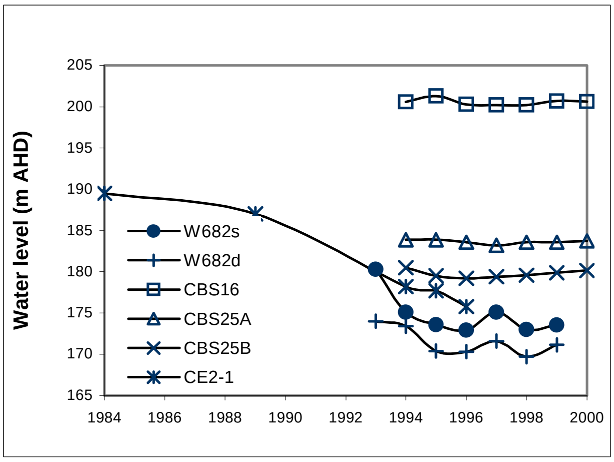


Figure 25. Hydrographs of the Muja aquifer, Cardiff Sub-basin

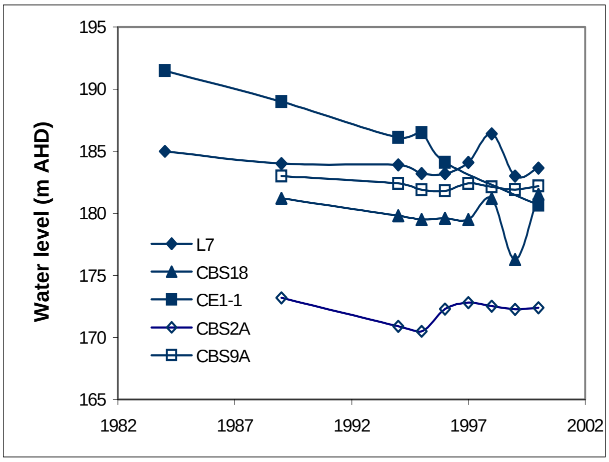


Figure 26. Hydrographs of the Premier and Allanson aquifers, Cardiff Sub-basin

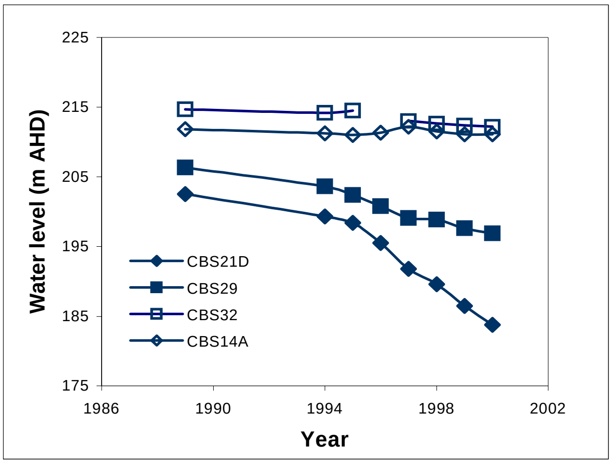


Figure 27. Hydrographs of the aquifers in Premier Sub-basin

of land during this period may have increased the rainfall recharge rates such that the net change in recharge may not be significant.

Data from 1998 onwards that include those from the CRM bores have been analysed to assess the regional variations in water levels in the Collie Basin between 1998 and 2000 (Figs 28 and 29). From 1998 to 1999, groundwater levels in the basin declined by an average of 0.3 m. The watertable decline occurred more in the areas of coal mining and abstraction for power station supply. In the Premier Sub-basin, decline was as much as 9.7 m in the coal mining area. Watertable in the southeastern part of the Cardiff Sub-basin near the Cardiff South wellfield declined by as much as 2.8 m. Recovery of up to 2 m in the watertable elevation was observed in the Muja aquifer of the Cardiff Sub-basin in the area of the pools; this is due to reduction in abstraction from the aquifer.

Between 1999 and 2000, there was an average recovery of the watertable in the Cardiff Sub-basin by 0.1 m. There was, however, a maximum recovery of 1 m near the area of the South Branch pools. Watertable near the Cardiff South wellfield declined by a maximum of 1 m. In the Premier Sub-basin there was an average decline in the watertable of 0.4 m. However, in the mining areas of the sub-basin water levels declined by a maximum of 5.5 m. During 2000–01, the average decline in the watertable in the Cardiff Sub-basin was 0.3 m, whereas in the Premier Sub-basin, the average decline was 0.2 m.

The overall change in storage based on changes in watertable elevation in Collie Basin for 1998–1999, 1999–2000 and 2000–2001 are estimated as $-14 \times 10^6\,\mathrm{m}^3$, $-2.5 \times 10^6\,\mathrm{m}^3$ and $-10 \times 10^6\,\mathrm{m}^3$ respectively adopting a specific yield of 0.15. These estimates are based on the change in storage in the shallow parts of the basin. In addition there may be changes in storage in the deeper parts of the basin that are not immediately observed at the watertable.

4.3 Impact of abstraction on river pools

Groundwater discharges into the Collie River and its tributaries, maintaining numerous river pools and wetlands. The river pools provide recreational opportunities for the community, serve as livestock water supplies to a number of farms, and provide a habitat for aquatic wildlife. However, pools in the Collie River South Branch that previously contained water throughout the year, have at times become dry each year during the last decade. The following excerpt from Lord (1952) based on his surveys in the Collie Basin during the late 1940s and early 1950s indicates that at that time the pools were maintained by groundwater throughout the year:

“The Collie River is the only river which drains the Collie area. The upper reaches of this and the other rivers do not flow throughout the year, but dry up into a series of pools. On the basin itself there are a few large pools, the biggest of which is Minninup, which like others has never been known to dry up. It is reasonable to assume that these pools are spring fed.”

Interpreted historical abstractions (Fig. 22) indicate that mine dewatering would have started impacting on the groundwater levels since the 1950s as a result of increased coal mining in 1952 from those seams of the Muja Coal Measures at Western 2 that lie beneath the river pools. The Long, Walkers, B. Cox, Cardiff and Grahams Pools overlie the Permian subcrop zones bounded by the Ben and Alpha seams that have been dewatered from the Western 2 and Western 6 underground mine, and the Piavininis Pool overlies the zone between the Wyvern and Collieburn 2L seams that have been dewatered from the Western 2, Western 6 and Western 7 mines.

A study by Morgan et al. (1995) on freshwater fish fauna in pools of the Collie River South Branch found the drying of a number of pools to have “enormous ramifications” on the ecology of the system and many fish deaths. A macroinvertebrates survey carried out by Halse et al. (1999) showed that the population in most river pools in the basin has lessened, and that the low pH of pool water may be a cause of this reduction. The maximum depth to the watertable below the South Branch pools at the end of summer is about 5 m at Piavininis Pool (Fig. 30, Table 10).

The watertable elevation near the pools following winter is 1–1.5 m above the end-of-summer levels. Groundwater levels remain below those of the river pools throughout the year at four of the seven significant pools along the South Branch. Only Chinamans Pool overflows as a result of natural groundwater discharge.

Groundwater flow in the eastern part of the Premier Sub-basin is towards Chicken Creek, whose confluence

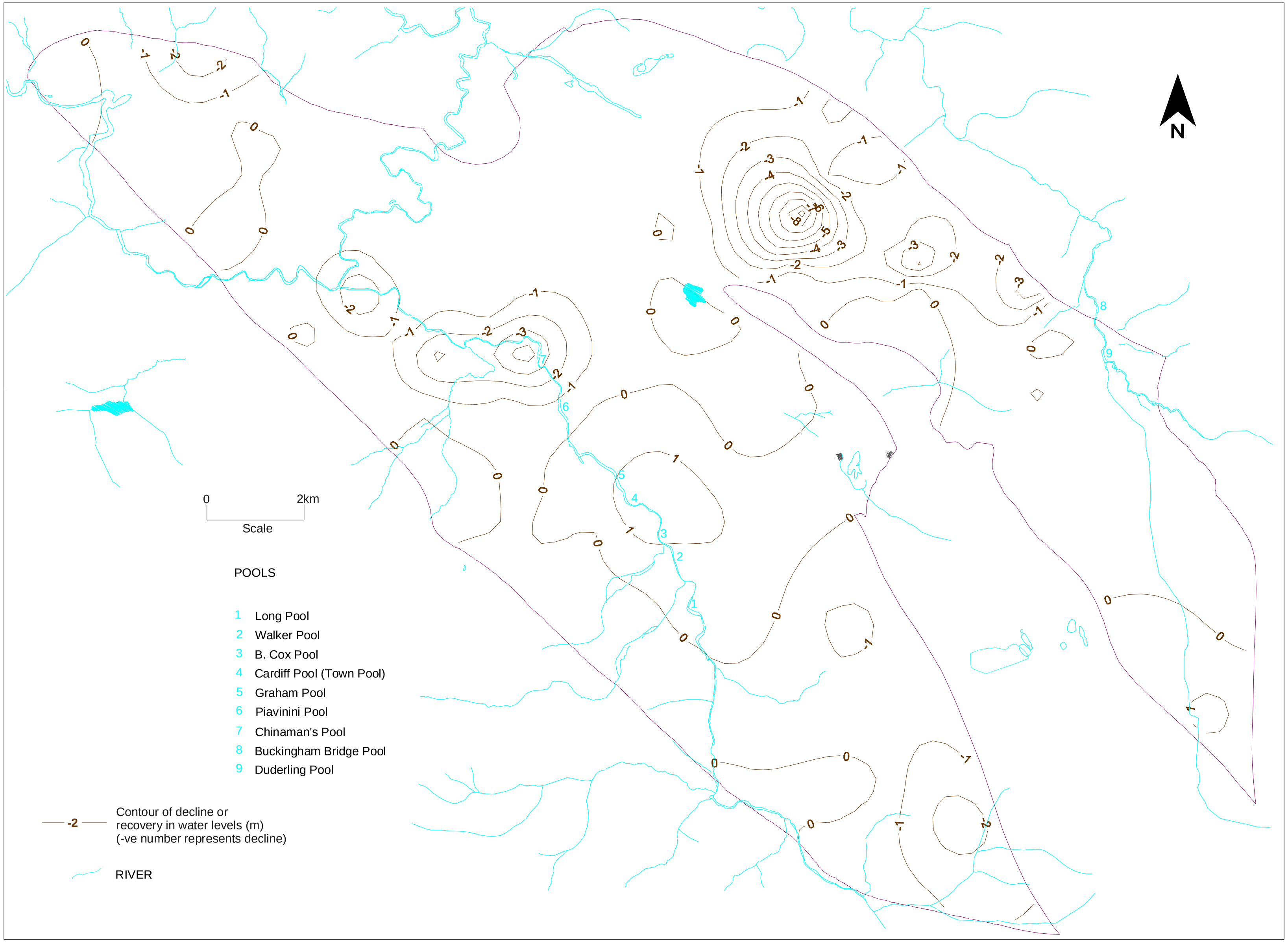


Figure 28. Water levels decline or recovery – 1998 to 1999

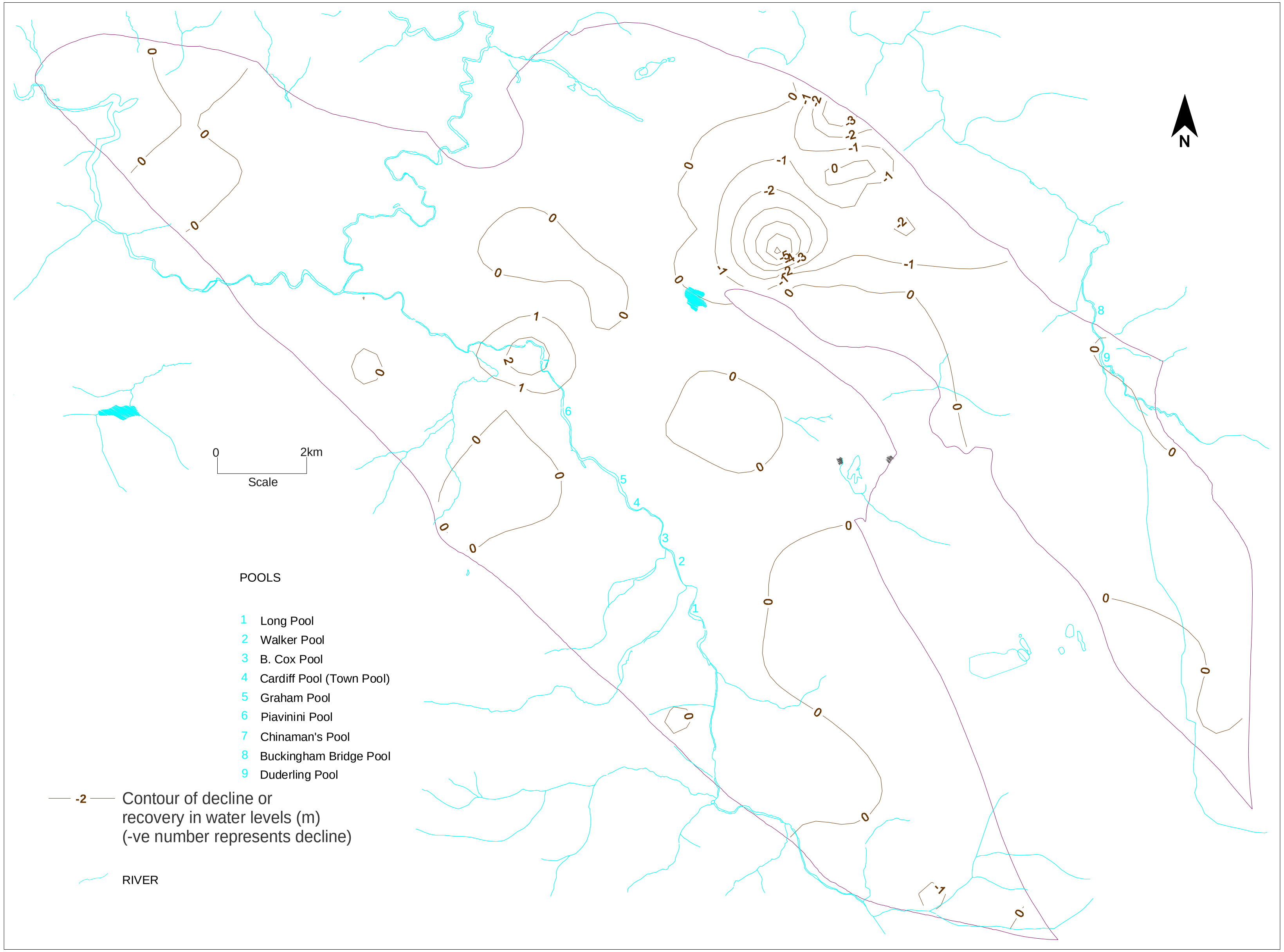


Figure 29. Water level decline or recovery – 1999 to 2000

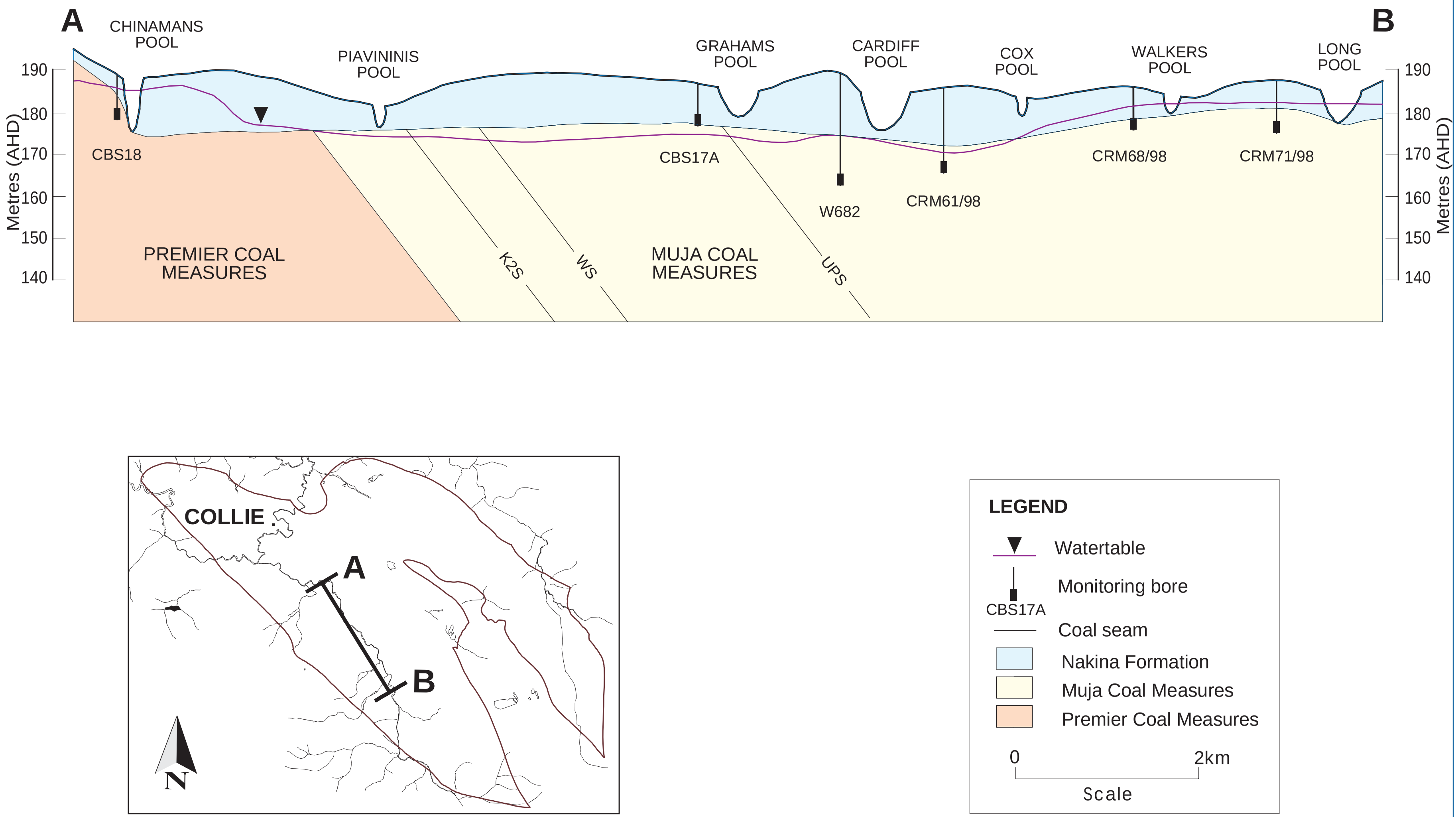


Figure 30. Hydrogeological section along river pools

with the East Branch is near the Buckingham Mills Pool (Pool 9). Historical groundwater levels (1984–1987) near the pool were higher than its pool cease-to-flow level indicating that the pool received groundwater discharge. Currently the watertable elevation is about 3 m below the cease-to-flow level of the pool.

Groundwater level in monitoring bores MX7 and CRM-45 at Pool 9 show a steady decline in response to dewatering at the adjacent Chicken Creek mine until 1997, after which there was significant reduction in abstraction due to cessation of mining, and a rise in water level was observed (Fig. 31).

As a large area of the Nakina Formation has been removed at the Chicken Creek mine, groundwater throughflow towards pools would have been significantly reduced, thus affecting the groundwater level near the pools.

4.3.1 Recovery of groundwater levels near pools of South Branch

Varma (1997) carried out an assessment of the change in storage of the Muja aquifer in the Cardiff Sub-basin from a conceptual pre-mining groundwater level and current water levels. He estimated that it would take as much as 30 years for the watertable to recover such that the pools of the South Branch could be maintained by natural groundwater discharge.

Typical hydrographs from a multiple piezometer in the Muja aquifer near Long Pool (Fig. 32) show significant recovery in the water level in the deeper piezometers (#3 and #2) since 1994 However, in the shallower piezometers (#5 and #4), there was an initial decline and thereafter minor recovery. This is primarily due to continued leakage of groundwater from the shallow parts of the aquifer to the deeper parts from which there has been large-scale abstraction.

Recovery rate will become faster when heads in the deeper parts of the aquifer exceed those in the shallow parts. This will happen with time as long as abstraction from the aquifer is significantly lower than recharge.

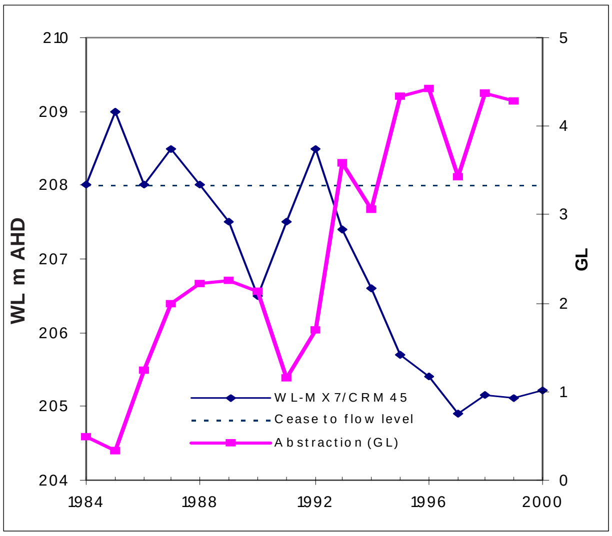


Figure 31. Groundwater level and abstraction adjacent to Buckingham Mills Pool

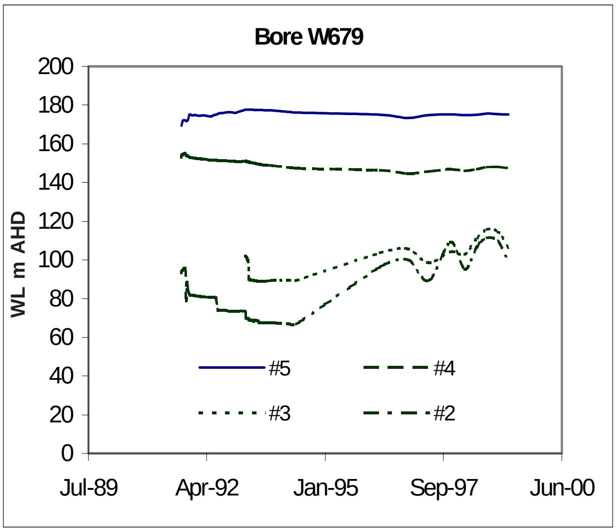


Figure 32. Hydrographs of bore W679 near Long Pool

Table 10. Interpreted watertable elevation near river pools

Pool	*Bed level (m AHD)*	*CTFL* (m AHD)*	*Watertable April-May 1998 (m AHD)*	*Watertable April 1999 (m AHD)*	*Watertable May 2000 (m AHD)*	*Recovery (1998-99) (m)*	*Recovery (1999-00) (m)*
Long	176.820	183.355	180.00	180.50	180.70	0.50	0.20
Walkers	177.763	182.180	179.00	179.75	179.95	0.75	0.20
B. Cox	179.338	181.238	175.00	176.40	176.90	1.40	0.50
Cardiff	172.510	177.000	170.00	171.25	171.85	1.25	0.60
Grahams	175.700	180.662	170.00	171.00	171.40	1.00	0.40
Piavininis	174.042	176.952	170.00	169.60	169.80	-0.40	0.20
Chinamans	172.300	176.273	178.00	177.40	177.50	-0.60	0.10
Buckingham Mills	204.800	208.200	205.15	205.11	205.22	-0.04	0.12

**Cease-to-flow level*

5 Water balance

5.1 General

The water balance of a system is established by identifying and equating all inflow to, and outflow from, the system. For the Collie Basin, both the surface water and the groundwater balance have been established. The components of the surface water balance of the Collie Basin are: surface water inflow from rivers and creeks, discharge of mine water, recharge to groundwater, discharge of groundwater to the rivers, and surface water outflow as river flow. The components of the groundwater balance are: rainfall recharge to groundwater, recharge to groundwater from river, groundwater discharge to rivers, evapotranspiration from watertable in areas where groundwater is shallow, and groundwater abstraction. As the component of change in aquifer storage in the Collie Basin can only be estimated using the post-1998 monitoring data (after construction of the regional monitoring bores), the water balance of the Collie Basin has been established for the period of May 1999 to April 2001.

5.2 Surface water inflow

Currently there are no stream gauging stations that measure surface water inflow to the Collie Basin. Surface water inflow to the basin has therefore been estimated using catchment yield coefficients that have been estimated by Dames and Moore (1996). Surface water inflow to Collie Basin takes place via the Collie River South Branch, Collie River East Branch and some minor creeks that flow into the Cardiff Sub-basin from the granitic terrain outside the basin. Runoff from within the basin is also a major component of the surface water balance.

5.2.1 South Branch catchment yield

The total catchment area of the Collie River South Branch is 668 km^2 of which about 25% is cleared. Dames and Moore (1996) estimated that recharge contributing to baseflow in the granitic terrain of the South Branch is 2% of the rainfall. Runoff from the cleared and uncleared parts of the catchment is 3.5% and 1.5% of the rainfall respectively. These equate to an average of 20×10^6 m^3/year for the period 1999 to 2001. Additional flow in the South Branch is generated by about 2×10^6 m^3 of water that is discharged to maintain summer flow in the river each year.

5.2.2 Inflow from Collie River East Branch

Gauging station S612035 on Collie River East Branch is located near the area where the river enters the basin. Streamflow records at the gauging station are, however, available only for the period 1955 to 1968. From 1995 onwards, due to commissioning of the Harris Dam, flow at this gauging station has been reduced. From correlation of flow at S612035, S612001 (further upstream on the East Branch) and S612036 (on the Harris River downstream of the dam), flow in the East Branch at S612035 is estimated as 120×10^6 m^3 for 1999 to 2001.

5.3 Surface water outflow

The Collie River is the only major drainage in the Collie Basin, which carries surface water outflow. Gauging station S612002, about 2 km downgradient from the basin margin, may receive about 1×10^6 m^3/year as extra runoff from outside the basin. Total flow at this gauging station during 1999 to 2001 has been recorded as 178×10^6 m^3. Total surface water outflow from the basin after discounting the runoff from the area outside the basin is therefore 176×10^6 m^3.

5.4 Groundwater recharge from South Branch and East Branch

The South Branch is mainly a losing river in its upstream part as the watertable is generally below the base of the river, apart from some pools in river where the watertable is higher than the pool bed. The East Branch is a losing river only in the southern part of the Premier Sub-basin. Leakage from the South Branch and the East Branch into the Collie Basin aquifers depends on the river stage, the hydraulic conductance of the river bed material, and the watertable elevation near the river. Little information is available about the river stage heights along the river, and hydraulic conductance of the riverbed material. It is thus difficult to calculate the leakage from the river. Groundwater modeling, however, shows that for river stages varying from 0 to 1 m and conductance per unit area varying from 0.01 to 1.0 $\mathrm{m}^2/\mathrm{day}/\mathrm{m}^2$, leakage from the river to the Collie Basin aquifers is about 1×10^6 m^3/year.

5.5 Groundwater discharge to the Collie River system

Groundwater discharge to the Collie River and its tributaries has been estimated as baseflow in the Collie River using the digital filtering technique provided by Chapman and Maxwell (1996). The baseflow separation of the streamflow in the Collie River at Mungalup Tower gauging station (S612002) shows that baseflow in the river from 1999 to 2001 was 14 × 10^6 m^3/year (Figure 33).

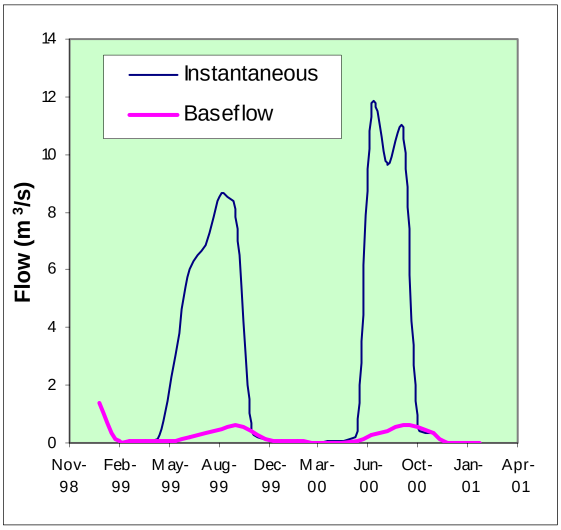


Figure 33. Baseflow separation for streamflow at S612002 on Collie River

Groundwater discharge to the river has also been estimated from the water balance of the Collie River and its tributaries. The river stage is lower than the surrounding watertable only in the section of the South Branch and East Branch downstream of gauging stations S612034 and S612035. Therefore the difference in the streamflow in Collie River at Mungalup Tower gauging station S612002, and the total of the flows at S612034 and S612035 and any runoff downstream of these two gauging stations (approximately 1 × 10^6 m^3/year) will be equal to the groundwater discharge to these rivers. The groundwater discharge to the Collie River and its tributaries within the basin is estimated as 8 × 10^6 m^3 and 6 × 10^6 m^3 for 1999/2000 and 2000/2001 respectively.

5.6 Surface water balance

The surface water balance of the Collie Basin is summarised in Table 11.

Table 11. Components of surface water balance

COMPONENT	*FLOW (x 10^6 m^3)* 1999–2001	*FLOW (x 10^6 m^3)* Average per year
INFLOW		
South Branch catchment yield (granitic terrain)	40	20
East Branch catchment yield	120	60
Mine discharge to South Branch	4	2
Groundwater discharge	14	7
Total inflow	**178**	**89**
OUTFLOW		
Collie River	176	88
River recharge to groundwater	2	1
Total outflow	**178**	**89**

5.7 Components of groundwater balance

Groundwater inflow is mainly from direct infiltration of rainfall and recharge from streams where the watertable is below stream-bed elevation. Groundwater outflow is from discharge to streams, evapotranspiration from the watertable in areas where the watertable is shallow, and groundwater abstraction. Groundwater balance is established by equating components of inflow and outflow with any change in storage, that is

$$\text{Inflow - Outflow} = \Delta \ \text{Storage}$$

Groundwater throughflow across the basin boundary is likely to be insignificant due to low transmissivity of the granitic rocks surrounding the basin.

5.7.1 Groundwater abstraction

Groundwater abstraction, including mine dewatering, in Collie Basin was 19 × 10^6 m^3 in 1999/2000 and 16 × 10^6 m^3 in 2000/2001. In addition, groundwater abstracted for other uses such as domestic and irrigation would have been about 1 × 10^6 m^3 for these two years.

5.7.2 Evapotranspiration from vegetation in areas of shallow watertable

Evapotranspiration from trees in areas of shallow watertable is a significant component of groundwater discharge. In the Collie Basin, the amount of groundwater uptake by vegetation directly from the watertable is about 1 × 10^6 m^3/year.

5.7.3 Groundwater recharge

Recharge by direct infiltration of rainfall as estimated by chloride mass balance is 12%; and by groundwater modeling as 19×10^6 m^3/year (10%). The recharge from modeling is, however, compatible with other components of groundwater balance (Table 12). In addition, there is about 1×10^6 m^3/year as recharge from the South Branch.

5.7.4 Change in storage

Change in groundwater storage in the Collie Basin aquifers for the period 1999 to 2001 is estimated as -12×10^6 m^3 based on monitoring of the overall change in watertable elevation and the corresponding storage based on a specific yield of 0.15.

5.8 Groundwater balance

The groundwater balance of the Collie Basin is summarised in Table 12.

Table 12. Components of groundwater balance

COMPONENT	*VOLUME(x 10^6 m^3)* 1999–2001	Average per year
INFLOW		
Rainfall recharge	38	19
River recharge	2	1
Total inflow (recharge)	**40**	**20 (10%)**
OUTFLOW		
Abstraction	36	18
Groundwater discharge to river	14	7
Evaporation from vegetation	2	1
Total outflow	**52**	**31**
Change in storage (inflow-outflow)	**-12**	**-6**

[*] Percentage of annual rainfall

6 Groundwater management issues

6.1 History of management

In 1988, the Water Authority of Western Australia (WAWA) released the first water resources management strategy for the Collie Basin (Water Authority of Western Australia, 1988). The document laid down policies for use of the basin water resources within the framework of Cabinet endorsements in 1982 that included

- Designation of coal mining as the primary land use in Collie Basin, whilst also recognising the need for this activity to be compatible with other land uses.
- Optimising coal recovery in such a way that there is a sustained use of the basin's other natural resources.
- Ensuring that coal mining and other activities in the basin do not significantly diminish the quality and quantity of surface runoff and recharge to the groundwater system, and that water resources are developed and utilised in the best interests of the State.

In summary, the 1988 water resource management strategies for the Collie Basin were

- As a priority, allocation of groundwater resources of Collie Basin will be primarily for power generation. Allocation will be administered by issuance of licences for groundwater abstraction.
- Groundwater may be allocated to other users provided this does not prejudice the priority use. Other users to be made aware that there will be no guarantee of continuity of water supply; that abstractions by priority users (power station and mining) are likely to lower groundwater levels significantly in future.
- Groundwater abstractions should be minimised in accordance with good water resources management in the following preferential order of use.
  1. Mine dewatering water
  2. 'Run of the river' water
  3. Groundwater from wellfields
- Effluent discharge to the Collie River system to be consistent with achieving the statutory water quality objectives for the Wellington Reservoir. These criteria precluded discharge of water having salinity exceeding 550 mg/L. The strategy recommended setting up of other quality criteria for maintaining potability of the reservoir water and the aquatic ecosystems of the stream channels.
- The strategy also required groundwater abstraction licensees to monitor all water abstractions, transfers and discharges, and behaviour of the groundwater resource and reporting to the Water Authority.
- Land subdivision or urban development to be subject to sewerage conditions unless it can be clearly demonstrated that such development will not adversely impact on the water resources.
- To continue work on quantification of the understanding of the hydrology of the Collie Basin, including monitoring of all components of the water cycle of the basin.
- Preparation of a draft Environmental Protection Policy designed to protect the environment, in particular the quality of surface water flows, and to achieve protection of the beneficial uses of the basin water resources.

The 1988 strategy was later modified to require restoration of livestock and domestic water supplies affected by major abstractions.

6.2 Groundwater use

6.2.1 Past abstraction

Groundwater use in the basin can be broadly categorised under power station use, discharge to rivers, and domestic/horticultural use. Discharge to rivers has been both to maintain flow and the aesthetic value of the rivers. Discharge to the rivers has mainly been from excess water derived from dewatering of underground and opencut mines that was not used for supply to the power station. Current domestic/horticultural use of groundwater is relatively minor at 0.42×10^6 m^3/year (Water and Rivers Commission, 2000). Table 13 provides a summary of the average annual groundwater use between 1984 and 1997 for power station supply and discharge to river. Data have been sourced from Dames and Moore (1997) and Dames and Moore (1998).

Table 13. Average annual groundwater use (major abstractions, 1984–1997)

Use	*Underground mines* (x 10^6 m^3/year)	*Shotts wellfield* (x 10^6 m^3/year)	*Cardiff South wellfield* (x 10^6 m^3/year)	*Opencut mines* (x 10^6 m^3/year)	*Totals* (x 10^6 m^3/year)
Power station supply	7.44	2.86	2.63	4.92	17.85
Discharge to rivers	3.61	-	-	4.24	7.85
Totals	**11.05**	**2.86**	**2.63**	**9.16**	**25.70**

Table 13 shows that groundwater abstraction for mining and power station supply has been at an average rate of 25.7 × 10^6 m^3/year of which 17.85 × 10^6 m^3/year has been supplied to the power station and 7.85 × 10^6 m^3/year has been discharged to the rivers.

An average of 9.16 × 10^6 m^3/year has been abstracted from the opencut mines. Underground mining ceased in 1994, after which discharge to rivers from underground mine water was reduced.

6.2.2 Future groundwater demand

Collie Water Advisory Group (1999) predicts that the power station water demand (excluding any recycled water) will be about 17.5 × 10^6 m^3/year between 2000 and 2004, and estimates that mine dewatering would meet 10.7 × 10^6 m^3/year in 2000 decreasing to 8.3 × 10^6 m^3/year in 2004. The remainder of about 6.8–9.2 × 10^6 m^3/year would need to be obtained from other sources. Other future groundwater uses include 3 × 10^6 m^3/year for new major industries (Collie Water Advisory Group, 1996), less than 0.4 × 10^6 m^3/year for domestic/ horticulture use, and about 0.4 × 10^6 m^3/year for maintaining water in pools.

6.3 Strategies for water resources management

In the summer of 1994/95, water level decline in some domestic wells, and the drying up of river pools of the South Branch and East Branch of the Collie River, gave rise to community concerns about the continued availability of the groundwater resource in the basin. In view of these concerns, future water requirements of the power station, and the need to deal with emerging groundwater problems in Collie Basin, Cabinet formed the Collie Water Advisory Group (CWAG) in 1995 to review the water resources management issues in the Collie Basin and recommend to Cabinet a strategic water-management plan, taking into consideration coal mining, power generation, future industry, and the environmental and social aspects.

As required, CWAG reviewed the water resources of the basin, and existing management strategies and, after a series of consultations with the stakeholders, developed the water-management principles and recommended several short-term and long-term strategies for the use of these resources. One of the key findings was that past abstraction of groundwater has led to a lowering of the watertable in the Cardiff Sub-basin and in the vicinity of the South Branch, thus adversely affecting some domestic water supply bores and the river pools.

Drying up of pools affected the fauna and recreational uses of these pools. In view of these findings, CWAG developed principles that reaffirmed the need to maintain secure and economic water supplies for power generation but which also promote the use of alternative water sources outside the basin in order to minimise groundwater abstractions within the basin.

Key short-term and long-term strategies included

- Use of the Wellington Reservoir and mine dewatering as primary supply to the power stations, thereby reducing the use of wellfields.
- Restoration of domestic/livestock water supplies affected by major abstractions.
- Artificial supplementation of the significant river pools.
- Further investigation of diversion of Collie River flow for recharging the Collie Basin aquifers and use of mine voids for storage and supply of water for power stations.
- A regional drilling and monitoring program for an improved understanding of the hydrogeology of the basin.
- A five year research on relevant water resources issues at $50 000 per year.

The CWAG recommendations/ strategies were based on an understanding that the water levels in the Cardiff Sub-basin, affected by large-scale abstraction, would recover within two to three years. However, a study by Water and Rivers Commission (Varma, 1997) estimated the recovery period as 30 years if no further abstraction takes place, and 100 years if abstraction continues at the post 1995 reduced rate. This finding and the need to artificially supplement the river pools for a longer period prompted the Government to reconvene CWAG in 1998. The reconvened CWAG reconsidered the long- and short-term strategies of 1996 and recommended that:

- The Water and Rivers Commission prepare an environmental-water provisions plan for long-term supplementation of the affected pools.
- Western Power Corporation adopt a suitable strategy for water supply to its power stations that minimises groundwater usage and impacts from wellfield by
  - Installation of infrastructure to ensure the supply of Wellington Reservoir water to both Muja and Collie power stations.
  - Use of Wellington Reservoir as a primary source for Collie Power Station. Harris Reservoir will be a primary source for the Collie Power Station until the end of 2000 when Wellington water supply infrastructure is in place. Thereafter, Harris Reservoir may be a backup source only.
  - Use of mine dewatering as a primary supply to Muja Power Station. Harris Reservoir and wellfields will be supplementary or backup sources. Beyond 2006, wellfields will only be used as emergency sources.
  - Use of groundwater from the Western 2 and 6 abandoned mines in the Cardiff Sub-basin only as backup sources up to the end of 2006, and as emergency sources only beyond this time.
  - When groundwater is required, preferential use of wellfields that impact least on South Branch river pools.

In December 1999, Cabinet endorsed the strategies of CWAG (1999).

A draft environmental provisions plan for the pools of the South Branch has been prepared (Welker Environmental Consultancy, 2001) based on assessment of ecological and social water requirements. The key features of the plan are summarised in Table 14.

Table 14. Environmental water provisions for South Branch pools
(Welker Environmental Consultancy, 2001)

FEATURE/VALUE	*REQUIREMENT*
All pools	**Winter/Spring**
Pool morphology	Maintain winter/early spring flow pool maintenance flow (met by the existing flow).
Water quality and macro-invertebrates existing flow).	Maintain pool connectivity during winter/spring (met by the
Fish	Pool connectivity during winter/ spring for fish migration and spawning (met by the existing flow).
Energy flows	Maintain pool connectivity during winter/spring (met by the existing flow).
Riparian vegetation	Season inundation during winter/spring for stimulation of seed-set (met by existing flow).
Seasonal adjustment	Flows to reflect ambient conditions and follow the natural hydrograph.
All pools except Piavininis and Chinamans Pools	**Summer/Autumn**
Water quality	Maintain individual pools during summer/autumn within 0.5 m of cease-to-flow. Maintain pH of any supplementation water above 5.5. Maintain dissolved oxygen level of supplementation water above 2 mg/L
Fish	As for pool water quality.
Macro-invertebrates	As for pool water quality.
Energy flows	As for pool water quality.
Riparian vegetation	Maintain pools within 1 m of cease-to-flow.

6.4 Pertinent groundwater management issues

During 2002–05, the Water and Rivers Commission plans to develop a detailed water resources management strategy for the entire Collie River Basin that will include the management of the surface water and groundwater of the Collie Basin. The strategy should take into account the need for long-term management of the river pools and impact of allocation on groundwater levels in the vicinity of the pools. However, the occurrence of groundwater of low pH near the pools, and its potential impact on pools ecology when the groundwater level recovers to discharge naturally into the pools, also need to be investigated to minimise any adverse impacts on the environment.

Management of abandoned mine voids and long-term impact on the groundwater resources should be considered, particularly in view of the potential of the overflow of poor-quality water into the South Branch. Outcomes of the ACARP projects regarding amelioration of acid in opencut mine voids will assist in management of the voids.

6.4.1 Artificial supplementation of river pools

As it will take several years for the watertable to recover in the Cardiff Sub-basin, the Collie Water Advisory Group has recommended consideration of long-term strategies for artificial supplementation of pools. Six of seven environmentally and socially significant pools of the South Branch and one pool of the East Branch will need to be supplemented artificially during cease-to-flow periods in the river. At Chinamans Pool groundwater level is sufficiently high to maintain the desired pool level, even in summer. Long Pool, Walkers Pool and Buckingham Mills Pool are maintained by groundwater discharge in summer, but the pool levels if not supplemented, decline below the cease-to-flow level.

The volume of water required to maintain the pools at a particular level is equivalent to change in storage of the pools at that level. The change in storage is due mainly to evaporation and leakage from the pools. The daily water requirement for maintaining the pools at a water stage height of ‘h’ is given as

$$V_m = A\,(h - h')\,c + A\,e \qquad (1)$$

V_m is the volume of water required (m^3/day)
A is the area of water surface (m^2),
h is the depth of water(m),
c is the conductance of the pool sediments per unit area (m^2/day/m^2),
e is the rate of evaporation (m/day), and
h' is the difference between the adjacent watertable elevation and pool bed. For all pools except Long, Walkers and Buckingham pools h' = 0 .

The conductance has been calculated from the leakage component of the pool water balance. This has been achieved by monitoring of pool water levels during summer to avoid any complexities in water balance due to the uncertainty in components of run-off, and surface water inflow and outflow at the upstream and downstream parts of the pools. The water balance components of the pools during the summer months are essentially the leakage from pools (L), evaporation from the water surface (E) and change in storage (∂s), and is written as

$$\partial s = L + E \qquad (2)$$

For pools that intersect the watertable, such as the Long Pool and Walkers Pool, leakage from the pool will occur only when the pool water level is higher than the adjacent watertable, and during this time there will not be any groundwater inflow to the pool. The leakage from the pool is dependent on the depth of water in the pool (h), area of the water surface (A) and the conductance of the pool-bed sediments (c).

$$L = A\,(h - h')\,c \qquad (3)$$

For the pools that intersect the watertable, the leakage will vary seasonally depending on the adjacent watertable elevation. Leakage will be maximum when the watertable is deepest as in April/May. Equation (3) is a variation of the relationship used by McDonald and Harbaugh (1988) in determination of interflow between river and aquifer. The evaporation from the pool will depend on the area of the water surface and rate of evaporation (e).

$$E = A\,e \qquad (4)$$

As the pools of the South Branch are generally semi-ellipsoidal in shape, the surface area of water will be directly proportional to the depth of water in the pool. Therefore, both leakage and evaporation would be directly proportional to the depth of water. As change in pool storage and evaporation can be directly estimated from the change in water levels, and evaporation can be estimated from meteorological data, the component of leakage can therefore be calculated. The conductance per unit area (c) can be calculated from leakage using equation (3) for each monitoring interval.

Table 15 provides the components of the losses due to leakage at the average of the initial and final water levels of the monitoring interval for each pool. The calculated values of streambed conductance per unit area are generally consistent for different areas of the pool beds (as a function of the water depth), but show a significant variation from one pool to another with conductance per unit area ranging from 0.006 to 0.07 m^2/day/m^2. The conductance of the pools appears to vary inversely with its size (product of length and depth) possibly because of deposition of a thicker layer of the streambed material in larger pools (Fig. 34). The average streambed conductance values are given in Table 16 along with the other physical data of the pools.

Table 15. Water balance components of the pools

Pool	*Date from*	*Dateto*	*Initial water level m AHD*	*Final water level m AHD*	*Average stage Height (h) m*	*Surface area (A) at h m^2*	*Storage change (∂s) m^3*	*Evap. (E) m^3/day*	*Leak. m^3/day*	*c m^2/day/m^2*
Long	14/11/97	24/11/97	183.44	183.19	6.50	9742	244	37	206	0.014
	24/11/97	03/12/97	183.19	182.97	6.26	9049	221	40	181	0.016
	08/12/97	15/12/97	182.76	182.65	5.88	7998	126	46	80	0.011
	22/11/99	26/11/99	183.53	183.44	6.67	10258	231	59	172	0.010
	26/11/99	29/11/99	183.44	183.35	6.57	9983	299	58	242	0.015
Walker	24/11/97	03/12/97	180.94	180.53	2.74	1327	60	6	55	0.056
	03/12/97	08/12/97	180.53	180.36	2.45	1239	42	6	36	0.065
	08/12/97	15/12/97	180.36	180.14	2.25	1182	37	7	30	0.100
	23/11/98	25/11/98	181.27	181.13	3.21	1474	103	7	97	0.055
	29/11/99	30/11/99	181.43	181.33	3.39	1532	153	7	146	0.069
B. Cox	08/12/97	15/12/97	180.14	179.87	0.66	49	2.0	0.3	1.7	0.049
	15/12/97	22/12/97	179.87	179.67	0.43	20	0.6	0.1	0.5	0.052
	22/12/97	29/12/97	179.67	179.48	0.24	6	0.2	0.0	0.2	0.084
Cardiff	14/11/97	24/11/97	175.57	175.24	1.91	6049	200	23	177	0.015
	24/11/97	03/12/97	175.24	174.61	1.43	5340	374	22	351	0.046
	03/12/97	08/12/97	174.61	174.40	1.01	4754	202	22	179	0.037
	23/11/98	25/11/98	176.64	176.55	3.10	7998	360	36	324	0.013
Grahams	22/12/97	29/12/97	179.81	179.61	3.21	7557	216	55	161	0.007
	29/12/97	05/01/98	179.61	179.46	3.04	7398	159	47	111	0.005
	05/01/98	12/01/98	179.46	179.25	2.86	7235	217	52	165	0.008
	12/01/98	10/02/98	179.25	178.74	2.50	6914	122	37	84	0.005
	10/02/98	16/03/98	178.74	178.04	1.89	6386	131	32	99	0.008
	16/03/98	23/03/98	178.04	177.99	1.52	6065	43	30	14	0.001
	23/03/98	30/03/98	177.99	177.89	1.44	6002	86	22	64	0.007
	30/03/98	13/04/98	177.89	177.69	1.29	5876	84	18	66	0.009
Piavininis	10/12/98	17/12/98	174.86	174.73	0.75	154	3	1	2	0.016
	17/12/98	31/12/98	174.73	174.33	0.49	65	2	0	2	0.048
	26/11/99	30/11/99	175.76	175.50	1.59	681	44	4	40	0.037
	30/11/99	03/12/99	175.50	175.37	1.39	522	24	4	20	0.028
	03/12/99	10/12/99	175.37	175.03	1.16	361	17	3	14	0.035
Buckingham Mills	23/11/00	25/11/00	207.98	207.96	3.06	3535	74	21	53	0.0027
	25/11/00	28/11/00	207.96	207.94	3.03	3502	77	21	56	0.0020
	28/11/00	30/11/00	207.94	207.92	3.02	3485	56	21	35	0.0018
	30/11/00	02/12/00	207.92	207.89	2.99	3441	86	27	59	0.0032
	02/12/00	04/12/00	207.89	207.87	2.97	3407	68	27	42	0.0023
	04/12/00	06/12/00	207.87	207.85	2.95	3375	81	26	55	0.0031

Table 16. Physical data of pools

Pool	*Cease-to-flow level (m AHD)*	*Max length (m)*	*Max width (m)*	*Bed level (m AHD)*	*Pool depth# (m)*	*Surface area# (sq. m.)*	*Pool volume# (m^3)*	*Bed conductance per unit area (m^2/day/m^2)*
Long	183.355	310	40.5	176.820	6.54	9861	32224	0.013
Walkers	182.180	74	31	177.995	4.18	1803	5036	0.069
B. Cox	181.238	29.5	17.2	179.338	1.90	398	379	0.062
Cardiff	177.000	300	37	173.500	3.50	8719	21370	0.028
Grahams	180.662	290	35	177.000	3.66	7972	23433	0.006
Piavininis	176.952	100	30	174.042	2.91	2356	3429	0.033
Buckingham Mills	208.200	268	18.5	204.800	3.20	3500	5267	0.002

#At cease-to-flow level

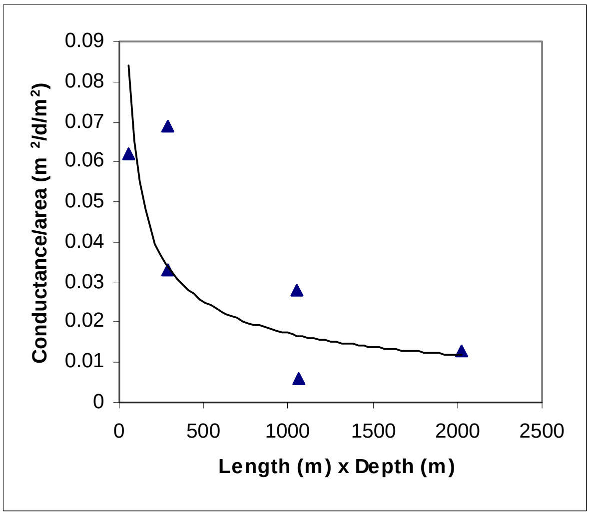


Figure 34. Variation of conductance per unit area with pool dimensions of the South Branch pools

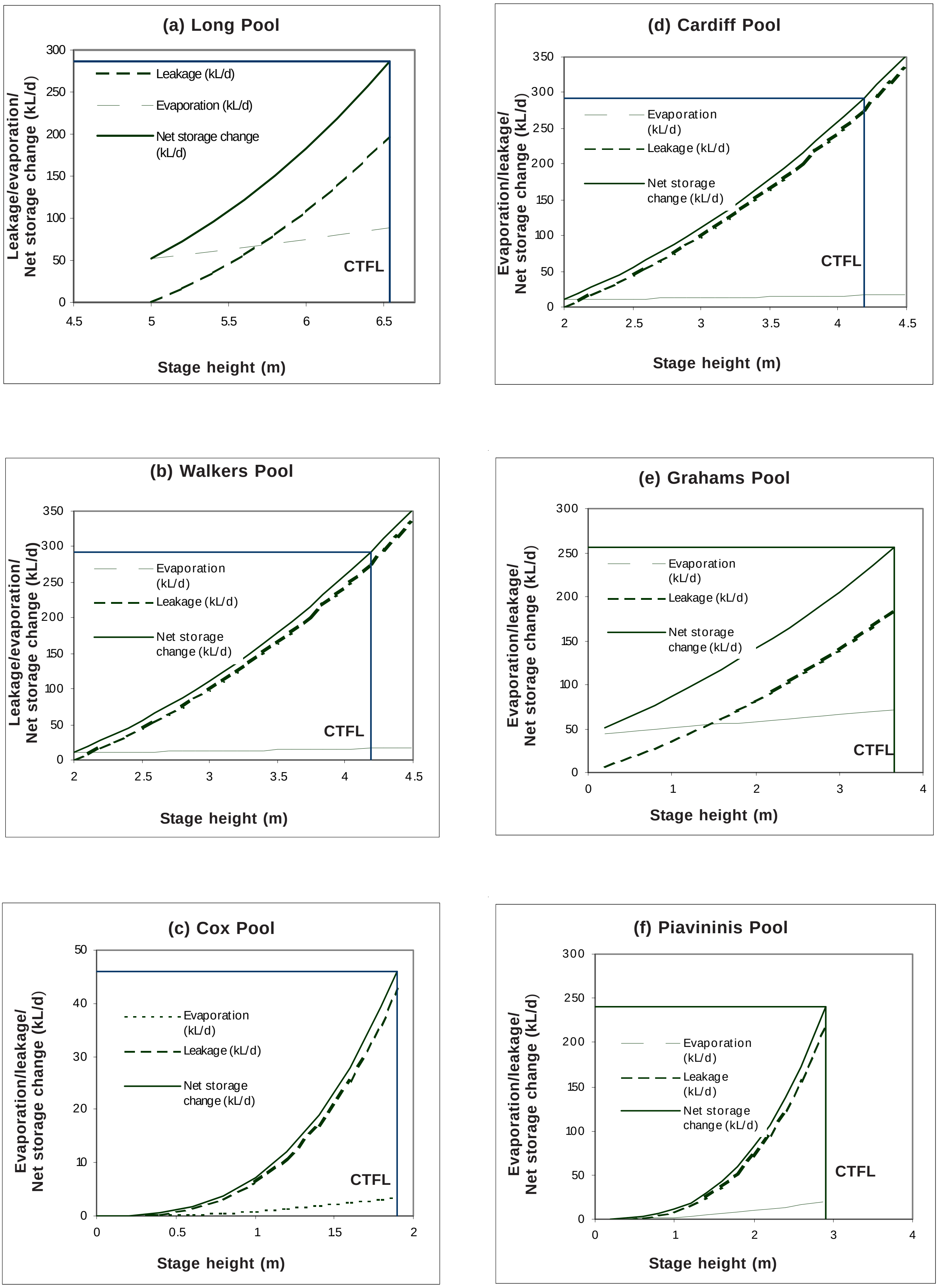
Graphs of water losses (equivalent to the water requirements to maintain pools) at different water levels have been generated using equation (4) for each of the pools (Figs. 35a–f). A peak summer evaporation rate of 9 mm/day has been adopted for calculating water requirements. The graphs show that the leakage component forms the major part of the net losses at cease-to-flow level, whereas losses due to evaporation are minor. The water requirements to maintain pools at cease-to-flow levels as interpreted from the graphs are given in Table 17. Cardiff Pool requires the largest volume of water for supplementation because of its large area and depth. Although Long Pool is the largest of the pools, the water requirement for maintenance at cease-to-flow level is relatively low because this pool receives groundwater and there is a low head difference between the groundwater level and the desired pool maintenance level, allowing lesser leakage. Owing to its low bed conductance, Grahams Pool requires relatively less volume of supplementation water in spite of its large area and depth. In the event that supplementation is not able to continue, for example due to temporary breakdown of pumping infrastructure, the water level in the pools will decline at a rate as defined by equation (1). Graphs showing the rate of decline of the pool water levels are shown in Figures 36a–f. If the water levels in the pools decline due to discontinuation of supplementation, pumping at rates higher than maintenance rates will be required to raise the water levels. This is due to concurrent water losses from leakage and evaporation while pumping water into the pools. Nomographs of water-level rise for different pumping rates are provided in Figures 37a–f. The graph for pool supplementation requirements for the Buckingham Mills Pool is given separately in Figure 38.

Table 17. Summary of pool supplementation requirements

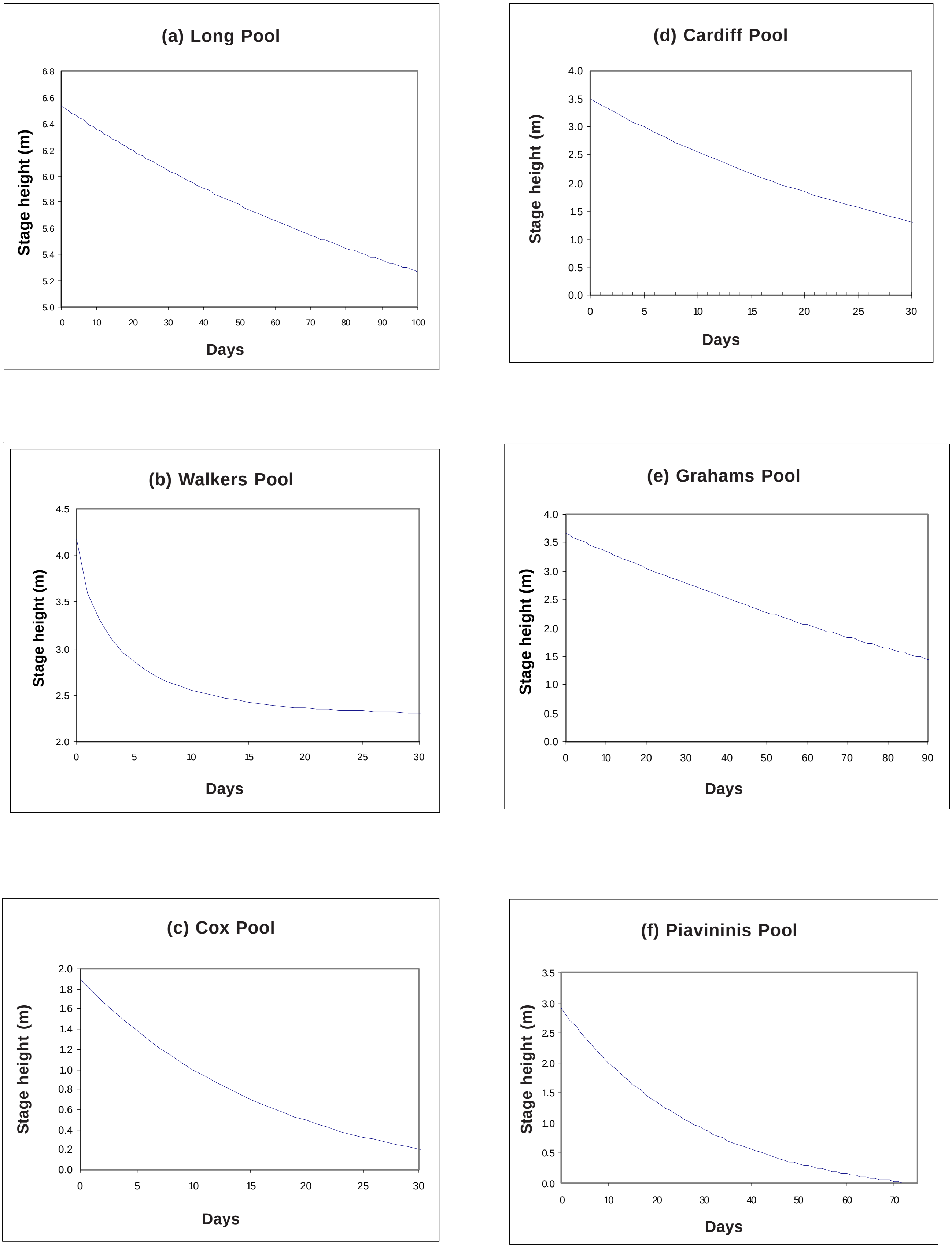
Pool	*Cease-to-flow level (m AHD)*	*Pool Depth[#] (m)*	*Water level requirement (kL/day)*
Long	183.355	6.54	287-427*
Walkers	182.180	4.18	292-380*
B. Cox	181.238	1.90	46
Cardiff	177.000	3.50	933
Grahams	180.662	3.66	256
Piavininis	176.952	2.91	240
Buckingham Mills	208.000	3.01	47-54*
Total			**2101-2336***

[#] At cease-to-flow level

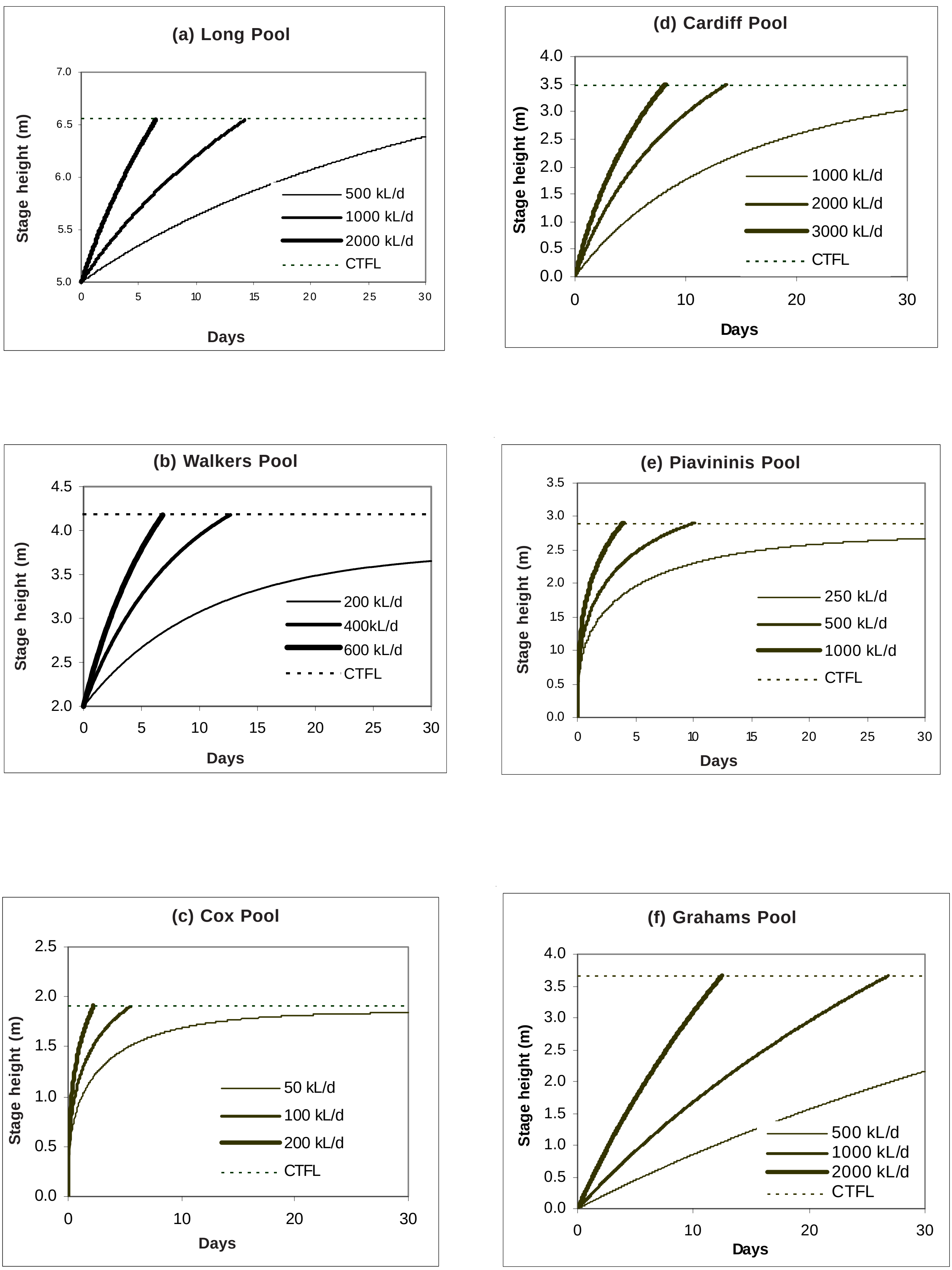
* Long, Walkers and Buckingham Mills pools will require more water in summer due to more leakage as a result of lowering of the adjacent watertable.



Figures 35. Pool supplementation requirements
(CTFL: Cease-to-flow level)



Figures 36. Water level decline in pools



Figures 37. Pool filling times
(CTFL: ***Cease-to-flow level)***

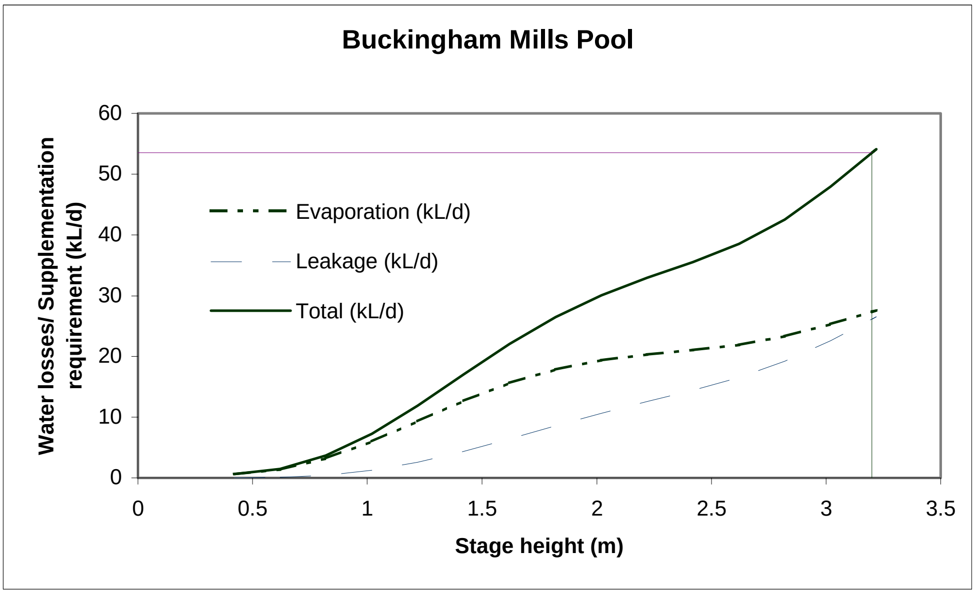


Figure 38. Buckingham Mills Pool supplementation requirements

6.4.2 Recovery of opencut mine void water levels

The Collie Basin has 14 opencut mines, many of these are no longer operational. The first group of opencut mines was closed in 1997. All the mines extend below the watertable and the original watertable configuration and groundwater flow patterns have been significantly altered as a result of dewatering. The closure of the Western 5 mine in the Cardiff Sub-basin involves six individual mine voids, the largest of which has a void area of about 920 000 m^2 and depth of 80 m. The voids, located alongside the South Branch, are now slowly filling with water. The proximity of the Western 5B mine void, the largest of these voids, to the river is an important issue in determining the closure options for this pit.

As a part of this study, a water balance and salt mass balance model of the Western 5B mine void has been developed using a computer program in BASIC programming language to predict void water levels and salinity based on different scenarios of streamflow diversion. The program listing is given in Table 18. The model takes into account water inflow from rainfall and runoff, groundwater inflow and streamflow diversion. The outflows include loss from leakage to groundwater, losses from evaporation, density-driven leakage and any overflow from the void when full. The model has been calibrated using the water-level monitoring data from 1997 to 2000 with a good correlation between observed and calculated data (Fig. 39). As the mine void receives both groundwater at depth as well as surface water runoff, it is expected that the water in the void will be well mixed. An example of a similar mine is the Pine Creek Gold mine in the Northern Territory that has a depth of about 100 m in which the water is well mixed (Parker and Robertson, 1999). Hence, for modeling it is assumed that there is no density gradient within the void. Density of the water in the void has been estimated from salinity using an algorithm developed by AGSO (Tucker and Evans, 1992).

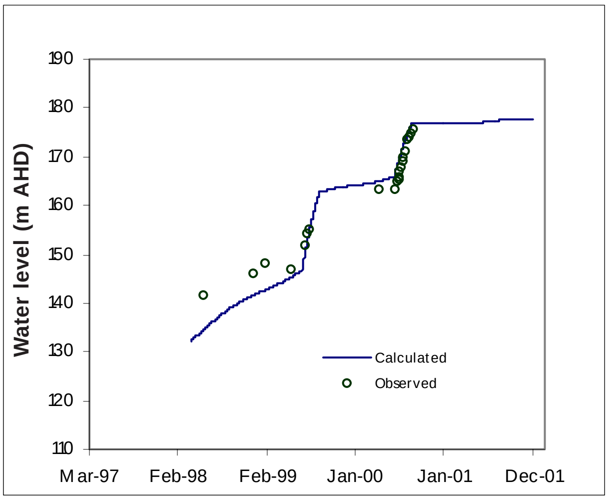


Figure 39. Western 5B void water balance model calibration

Table 18. Program listing – Western 5B void water balance simulation

```
100 REM PROGRAM CALCULATES THE WATER
     BALANCE OF WO5B VOID-COLLIE BASIN
110 REM PROGRAM BY S VARMA - WATER AND
     RIVERS COMMISSION
120 PRINT: PRINT
130 CLS:KEY OFF
140 DIM R(365),E(365)
150 YT=100
160 F1=5:Y1=6
170 F2=0:Y2=YT-Y1
180 K=.0007
190 RC=.3
200 RH=73
210 PRINT”————————————————————
    ——————————”
220 PRINT”Program will calculate the yearly water
    balance for WO5B mine void”
230 PRINT”with following specifications:”
240 PRINT:PRINT”Total years: “;YT
250 PRINT”streamflow diversion: “
260 PRINT F1;” GL/year for “;INT(Y1);” years”
270 IF Y1=YT THEN 290
280 PRINT F2;” GL/year for remaining “;INT(YT-Y1);
    “years”
290 PRINT”————————————————————
    —————”:PRINT
300 INPUT “Enter output file name (without extension):”,
     FI$
310 OPEN FI$ FOR OUTPUT AS #2
320 PRINT #2, “Water Balance simulation for WO5B
    mine void for “;YT;” years
330 PRINT #2,”streamflow diversion: “
340 PRINT #2, F1;” GL/year for “;INT(Y1);” years”
350 IF Y1=YT THEN 370
360 PRINT #2,F2;” GL/year for remaining “;INT(YT-Y1);
    “years”
370 PRINT #2,
380 PRINT #2, “Year”,”GW”,”Runoff”,”Evap.”,
    “Rain.”,”SFL”,”Leak.”,”Level”,”TDS”,
     “Overflow”
390 FOR I=1 TO 31: E(I)=-9.100001: R(I)=.5: NEXT I
400 FOR I=32 TO 59: E(I)=-8.600001: R(I)=.55: NEXT I
410 FOR I=60 TO 90: E(I)=-6.8: R(I)=.8: NEXT I
420 FOR I=91 TO 120: E(I)=-4.2: R(I)=1.6: NEXT I
430 FOR I=121 TO 151: E(I)=-2.7: R(I)=4.12: NEXT I
440 FOR I=152 TO 181: E(I)=-2.1: R(I)=6.13: NEXT I
450 FOR I=182 TO 212: E(I)=-2!: R(I)=5.85: NEXT I
460 FOR I=213 TO 243: E(I)=-2.4: R(I)=4.54: NEXT I
470 FOR I=244 TO 273: E(I)=-3.2: R(I)=3.32: NEXT I
480 FOR I=274 TO 304: E(I)=-4.5: R(I)=2.14: NEXT I
490 FOR I=305 TO 334: E(I)=-6!: R(I)=1.08: NEXT I
500 FOR I=335 TO 365: E(I)=-7.8: R(I)=.51: NEXT I
510 PRINT:PRINT
520 PRINT”Running simulation...please wait”
530 PRINT: PRINT
540 Q=0:Y=1:D=60:TD=600:H=0
550 CG=0:CO=0:CE=0:CR=0:CS=0:CL=0:OF=0
560 A=119.78*H^2+2064.8*H+15063
570 RO=(920315!-A)*RC*R(D)/1000
580 IF RO<0 THEN RO=0
590 CO=CO+RO
600 F=.9-((80-H)*.0025)
610 E=E(D)*F*A/1000
620 CE=CE+E
630 R=R(D)*A/1000*.8
640 CR=CR+R
650 IF D<181 OR D>250 THEN 700
660 IF Y<3 THEN 700
670 IF Y>Y1 THEN 690
680 SF=F1*1000000!/70: GOTO 710
690 SF=F2*1000000!/70: GOTO 710
700 SF=0
710 CS=CS+SF
720 P=.998+(.0000007*TD)-(2E-13*TD^2)
730 HF=P*H/(.9985)
740 IF HF<RH THEN LK=0: GOTO 760
750 LK=(A+758180!)*(HF-RH)*K*.5
760 CL=CL+LK
770 GW=A*(RH-HF)*K
780 IF GW<0 THEN GW=0
790 CG=CG+GW
800 B=GW+RO+E+R+SF-LK
810 Q=Q+B
820 H=H+B/A
830 IF H>80 THEN 960
840 VD=0
850 OF=OF+VD
860 TD=(((Q-B-VD)*TD)+(740*GW)+(200*RO)+(1200*SF)+
     (10*R)-(TD*LK))/(Q-VD)
870 IF D=365 THEN 900
880 D=D+1
890 GOTO 560
900 PRINT #2, Y,CG,CO,CE,CR,CS,-CL,110+H,TD,OF
910 D=1:Y=Y+1:CG=0:CO=0:CE=0:CR=0:CS=0:CL=0:
     OF=0
920 IF Y>YT THEN 940
930 GOTO 560
940 PRINT “Simulation completed - Open output file to
     view results”
950 END
960 VD=(H-80)*A
970 H=80
980 GOTO 850
990 END
```

From regression it has been established that for salinities less than 300 000 mg/L, the density (ñ) will vary according to the relationship:

$$ñ = (-2e\text{-}13 \times TDS^2) + (7e\text{-}07 \times TDS) + 0.998$$

This relationship has been used in the water balance model to calculate density driven flows from the void by calculating the equivalent pressure head at the salinity of the groundwater surrounding the void.

For the purpose of modeling, a runoff coefficient of 0.3 has been taken Dames and Moore (1996) for calculation of mine site runoff. A conductance per unit area of 0.0007 m^2/day/m^2 has been used for calculating groundwater inflow to and leakage from the Western 5B void. Long-term means of monthly rainfall and evaporation have been used for the water balance model. Physical dimensions of the void have been obtained from Dames and Moore (1996). A pan coefficient range of 0.7 to 0.9 has been used and made to vary linearly with depth, with the highest value applied when the water is at the surface (190 m AHD) and the least when the water level is near the floor of the void (110 m AHD). The aquifer surrounding the void has been assumed to be homogeneous and isotropic, and a fixed head of 183 m AHD has been used within the aquifer. The salinity of groundwater surrounding the void has been taken as 740 mg/L.

Water balance modeling shows that the water level and salinity in the Western 5B void will depend on the amount of streamflow diverted into the void. Results of modeling are given in Appendix IV. Since July 1999, about 5×10^6 m^3/year of streamflow has been diverted to the Western 5B void under a rapid-filling program by Wesfarmers Coal. With a streamflow diversion of 5×10^6 m^3/year each year, it is expected that the void will overflow in the winter of 2003.

Figure 40 shows that cutting off streamflow diversion completely after the Western 5B void is filled up will cause the water level in the void to decline to about 8 m below the overflow level (190 m AHD) within 10 years, after which the rate of decline will be much slower. Under either option, long-term salinity will be between 1200 mg/L and 2500 mg/L (Fig. 41). It is unlikely that any density-driven flow will take place under these salinities. However, some increase in the salinity of the groundwater due to diffusion may take place locally.

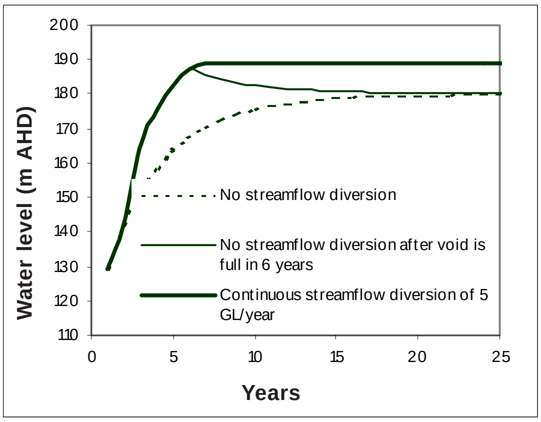


Figure 40. Predicted Western 5B void water levels

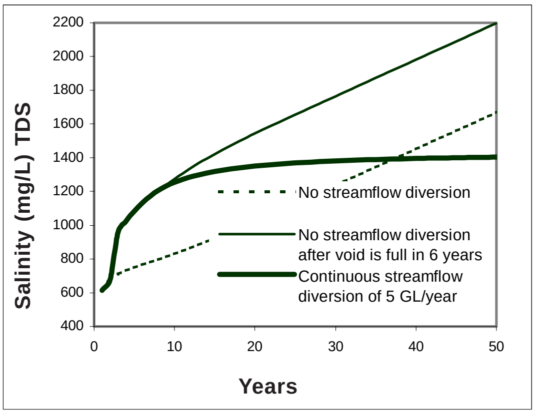


Figure 41. Predicted Western 5B void salinity

If streamflow diversion is continued over the long-term at 5×10^6 m^3/year when the void is full, there will be an overflow of about 3×10^6 m^3/year will take place. At that stage, streamflow diversion could be reduced to 2×10^6 m^3/year to avoid any outflow from the void while still maintaining a high water. Void salinity will increase to about 1400 mg/L in 50 years, after which it will remain nearly constant. Under either of these scenarios, about 1.8×10^6 m^3 of void water of salinity 1200–1400 mg/L will leak into the groundwater each year (after the void is full), enhancing recovery of groundwater levels significantly but increasing the salinity. As the mine void and the river pools lie in areas of different aquifer zones separated by coal seams and shale of low permeability, the effect of this extra recharge to the recovery of groundwater levels will initially be limited to the area closer to the mine void. The effect of this extra recharge near river pools will be observed only when water levels near the voids have risen to above the base of Nakina Formation so that increased lateral flow towards the pools can take place.

It is not possible to predict the pH of the void water using the model. The pH derived from the water balance model based on mixing of water of different pH, and assuming no further production of acid, shows higher values than the observed pH (Fig. 42). This indicates that there is a significant amount of acid being produced from the mining waste that has been used to partially backfill the voids. It is expected that as the water level in the void rises and comes into contact with more backfill material, more acid will continue to be produced until the void is completely full of water. Eventually, the acid-producing capacity will be restricted due to reduced oxygen conditions beneath the water surface, and the pH will gradually increase to that in the river, provided acid mine drainage from adjacent waste dumps is restricted.

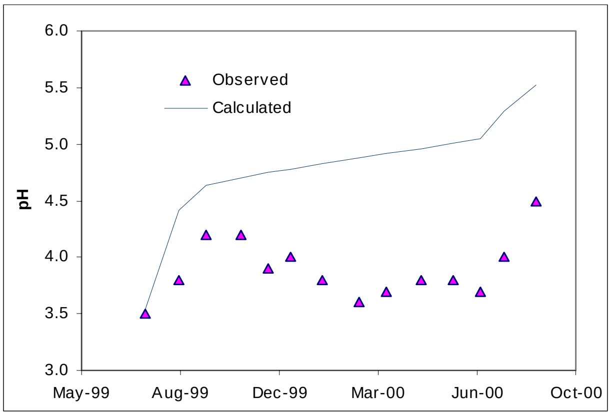


Figure 42. Comparison of observed and calculated pH of Western 5B void

Quantitative assessment of the acid-producing capacity of the backfill material is beyond the scope of this study, but could be taken up separately. A study of the trends in pH of the void water is important for management of the voids. Overflow of low pH water from the void into the Collie River South Branch, that eventually flows into the Wellington Reservoir, is potentially unacceptable. Flow of low pH water in the South Branch could also adversely affect the river environment. Consequently, it may be more appropriate to control streamflow diversion to the void in order to maintain water levels such that there is no overflow. Assuming the pH of the overflow water as 4, at the gauging station S612034 in the downstream part of the South Branch where the mean annual and streamflow is 30 × 10^6 m^3/year, the resultant pH due to mixing of the overflow water and the undiverted river water (having nearly neutral pH) will be about 6.5. While the resultant pH may be within acceptable limits, the suspended backfill material and concentrations of any toxic trace elements should be considered prior to taking a decision as to whether to allow any overflow. It would be more appropriate if the overflow water (3 × 10^6 m^3/year) could be utilised for power station supply subject to its meeting the quality criteria. This would reduce the demand on groundwater resources of the basin.

6.4.3 Quality of groundwater discharge to the Collie River

The occurrence of groundwater of low pH near the Collie River South Branch, and its potential downstream impact when the groundwater level recovers to discharge naturally into the river, will need to be investigated. Discharge of acidic groundwater into the river is of particular significance to the Wellington Reservoir water quality and the river ecology. Although the groundwater that discharges into the river is acidic, the salinity of the groundwater is fresh and affects the salinity of the river. Total dissolved solids (TDS) and pH were monitored at the different pools of the South Branch in various months of 1997–1998. Table 19 provides a summary of the water quality in summer and winter of 1998. In winter, when the surface water level in the pools is higher than the adjacent groundwater level, monitoring data show that in general the salinity of groundwater that is recharged from the South Branch is brackish. This is evident from the salinity of groundwater in the vicinity of the South Branch (Fig. 18). The pH of the South Branch water is generally neutral.

Table 19. Water quality of South Branch pools

Pool	pH		TDS (mg/L)	
	#	*	#	*
Long	3.1	7.4	1146	3207
Walkers	3.3	7.7	1199	3052
B. Cox	3.7	7.3	1188	3141
Cardiff	Dry	7.2	Dry	3069
Grahams	6.9	7.1	3652	3089
Piavininis	Dry	6.8	Dry	3323
Chinamans	6.6	6.8	468	3154

[#] Summer 1998, [*] Winter 1998

Data show that the pH of some pools is acidic in summer. However, in winter when there is streamflow, pH of stream water at all pools is neutral to marginally alkaline. The Long, Walkers and B. Cox pools have noticeably lower pH in summer. These pools are in the vicinity of underground coal mines and the pH of groundwater in this area is generally between 2.5 and 5, indicating that pools receive groundwater discharge in summer. Grahams Pool has a neutral pH even in summer, possibly due to its low bed conductance, and therefore its ability to retain surface water for longer periods. The salinity of the pool water is also high (3652 mg/L TDS) from concentration due to evaporation. Chinamans Pool is maintained by natural groundwater discharge in summer and, as it is further away from the area of low pH groundwater, the pH of pool water in summer is higher than in other pools.

The salinity of the upstream part of the South Branch water during winter flows is brackish (>3000 mg/L) representing the TDS of surface water runoff from the saline catchment of the South Branch. In summer, the salinity of the water in the pools is much lower (<1200 mg/L) representing the salinity of the groundwater, which is generally fresh to marginal in that part of the Collie Basin. The salinity of South Branch water at gauging station S612034, which is in an area of potential groundwater discharge, varies on average from about 400 mg/L in summer to around 2500 mg/L in winter (Fig. 43). The summer salinity represents the salinity of the basin groundwater that discharges into the river in this area.

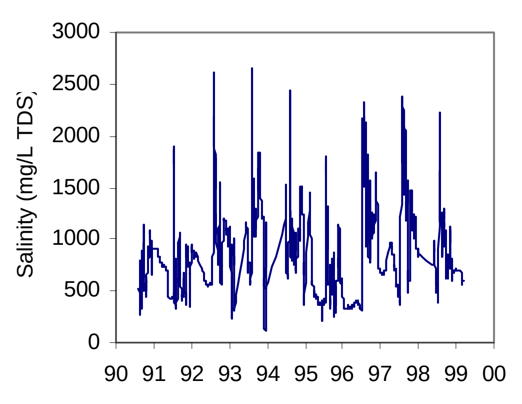


Figure 43. Salinity variation in South Branch

In the Collie Basin, discharge of groundwater to the Collie River and its tributaries is a major outflow component of the groundwater balance. Discharge to the Collie River system takes place mainly in the northwestern part of the basin. Some discharge also takes place as groundwater flow to Long Pool and Walkers Pool.

The volume of groundwater discharging into the Collie River, South Branch, and East Branch has been estimated as 7×10^6 m^3/year and is currently about 8% of the total flow in the Collie River at Mungalup Tower gauging station (S612002). Mean annual salinity at this station in recent years has been approximately 1500 mg/L TDS. Average salinity of groundwater in the area of potential discharge to the Collie River is about 200 mg/L TDS. Groundwater discharge to the Collie River, therefore, results in a 7% reduction of salinity in the Collie River.

Groundwater modeling shows that if groundwater levels in the basin were allowed to recover to pre-mining water levels, groundwater discharge to the Collie River would be 16×10^6 m^3/year which would cause a lowering of the salinity in Collie River by as much as 15%.

In areas surrounding the Collie River and its tributaries, where groundwater discharge to the river takes place, the pH of groundwater ranges from 5 to 6. It is unlikely that discharge of such groundwater will have any significant effect on the average pH of the Collie River under current groundwater discharge volumes.

In the upstream part of the South Branch, groundwater of pH as low as 2.5 discharges into Long Pool and Walkers Pool in summer when the pool stage is below the adjacent groundwater level. Discharge of low pH groundwater has caused reduction in population of macroinvertebrates in these pools (Halse et al., 1999). As groundwater levels rise in the Cardiff Sub-basin, due to cessation of coal mining, increased discharge of low pH groundwater into the South Branch will occur. An assessment of the potential impacts of such groundwater discharge on the river/pool fauna and riparian vegetation should be carried out so that remedial measures can be undertaken if required.

After complete recovery of the groundwater levels in the basin, it is expected that groundwater discharge to the Collie River of about 16×10^6 m^3/year will have an average pH of around 4, however, further work will be required to determine the long-term pH accurately. Based on simple mass balance, such discharge will cause a reduction in pH of the Collie River water from currently neutral to about 6.5. When groundwater levels in the Cardiff Sub-basin recover to cause substantial discharge into the South Branch, the river pH will be significantly lower in summer when flow will consist mostly of baseflow from groundwater discharge.

In addition to the discharge of low pH groundwater into the Collie River system, overflow of acidic water from the abandoned opencut mine voids could take place as streamflow is diverted into the voids under a "Rapid filling program". Downstream impacts of such overflow will need further investigation.

Acidic groundwater can mobilise potentially toxic pollutants, such as As, Be, Cu, Mo, Ni and U, associated with the Collie Basin coal. Although these could discharge into the Collie River, concentrations are likely to be low.

6.5 Research and monitoring

Based on the recommendations of the Collie Water Advisory Group (1996) the State Government has allocated $50 000 per annum for five years to be used for supporting research to enhance water resource management in the basin. Since 1997, the funds have been provided for relevant research upon recommendations of the Collie Basin Research Steering Committee established for advising Water and Rivers Commission on selection of projects for research.

The Collie Basin Research Steering Committee has representatives from key Government agencies, the Shire of Collie and major users of Collie Basin groundwater, and is chaired by Water and Rivers Commission. The committee has identified the following issues as the key focus for research in the Collie Basin

- Groundwater recovery
- Sustainable use of groundwater resources in future
- Management of river pools
- Ecosystem and social issues

The committee has so far undertaken the following projects

- Audit of geological, hydrogeological and hydrological data of the Collie Basin by Water and Rivers Commission.
- Age dating of groundwater in the Collie Basin, using Carbon-14 and CFC concentrations, by CSIRO (Turner et al., 1999).
- Monitoring of water quality in the Collie Basin – Macroinvertebrates and the AusRivas approach by CALM (Halse et al., 1999).
- Cardiff Sub-basin conceptual groundwater model by Aquaterra Consulting (Aquaterra, 1999).
- Three-dimensional numerical groundwater flow modeling of the Collie Basin by Geo-Eng (Australia) Pty Ltd and Water and Rivers Commission (Varma and Zhang, 2002).

These projects have made significant contributions to an improved understanding of the water resources of the basin. The groundwater modeling in particular will provide an important management tool in order to

- understand the local and regional impacts of mine dewatering and other groundwater abstraction;
- gain an improved understanding of the groundwater–river interaction to aid river pool augmentation;
- assess options for enhancing recovery of groundwater levels, including artificial recharge; and
- assess options for rehabilitation of opencut mine voids.

As mining and large-scale groundwater abstraction are likely to continue for the next 30 years, monitoring of hydrological and hydrogeological parameters will be required to facilitate research to support efficient long-term management of the water resources of the basin. It will be necessary to continue monitoring the water levels in the bores for continued assessment of the impact of mining and groundwater abstraction for power generation. It is recommended that the regional monitoring bores be monitored for water level twice a year to obtain peak minimum and maximum water levels. Salinity and pH in these bores should be monitored annually in summer. Apart from these activities, monitoring specific to the groundwater licence conditions and environmental water provisions should be carried out as required.

It is recommended that a review of the hydrogeology of the basin is carried out every five years taking into account new data and any advancement in the science that may aid further assessment of the complex hydrogeology of the basin. Study of acid mine drainage from the waste dumps and acidification of rehabilitated mine voids in the Collie Basin should be undertaken to assess future downstream impacts of these voids. These would require regular monitoring of physical and chemical parameters of the void water and of the surrounding groundwater. As a part of the Australian Coal Association Research Program (ACARP), Curtin University of Technology is undertaking a multi-disciplinary research project to develop appropriate low cost and low maintenance technology for rehabilitating acid water to treat the water in the mine voids. Possibilities of using the voids for aquaculture are being investigated at Ewington II opencut mine void (Phillips et al., 2000). Several sub-projects of the research program include

- geology, geochemistry and hydrogeology of the area,
- amelioration of acid runoff from coal mine dumps,
- passive mine drainage treatments and aquatic vegetation strategies, and
- bacterial strategies for increasing pH in acidic voids.

Outcomes of this research project will greatly assist in management of the abandoned mine voids in the Collie Basin.

There is a need for a coordinated ‘whole of the basin approach’ in monitoring and reporting of hydrogeological data and assessments on local and regional scale by the major users of the groundwater of the basin. Such an approach will maintain integrity of data and facilitate data retrieval from a central source. Data collated as part of the Collie Basin groundwater modeling project should be taken up by the WIN database of Water and Rivers Commission, and ld continue to be updated with both point-source and time-series data for ready use for future hydrological/hydrogeological research.

7 Conclusions

An investigation comprising drilling and monitoring of bores has permitted a better understanding of the hydrogeology and groundwater resources of the Collie Basin for management of these resources and the associated environment.

An improved understanding of the hydrogeology of the basin has been developed based on literature review and analysis of drilling, testing and monitoring data. The hydrostratigraphy of the basin has been defined and a new aquifer nomenclature has been proposed. Components of both surface-water and groundwater balance of the Collie Basin have been determined.

Based on data from about 140 monitoring bores in the basin, a synoptic watertable contour map has been prepared, and has formed the basis for a study of the shallow groundwater flow in the basin. The regional groundwater flow direction in the Collie Basin is changed from a conceptual pre-mining flow scenario because of mine dewatering and large-scale groundwater abstraction for power generation.

Recharge to the basin from direct infiltration of rainfall is estimated as 19 x 10^6 m^3/year. In addition there is 1 x 10^6 m^3/year of recharge from the South Branch. Recharge to the basin equates to about 14% of annual rainfall. The volume of groundwater in storage is about 7100 x 10^6 m^3. However, economics and policies preclude abstraction at this level. Recharge to and flow through each Permian aquifer under pre-mining steady state and present transient conditions have been estimated from a 3D groundwater flow model using MODFLOW and GMS.

Assessment of the impact of large-scale groundwater abstraction in the basin on groundwater levels has been carried out. In the past, annual groundwater abstraction from the basin has significantly exceeded recharge, causing a basin-wide decline in water levels. In places, the watertable is as much as 5 m below the base of the South Branch river bed. As a result, some river pools of the South Branch that were previously maintained by natural groundwater discharge are now dry in summer. It is estimated that it would take around 30 years for the watertable to recover so that pools can be maintained by natural groundwater discharge. However, since 1995, after closure of the underground mines and subsequent reduction in groundwater abstraction, water levels in some parts of the basin, including the area of the pools, have been rising.

Analytical techniques have been used to determine bed conductance of the pools. Based on the pools water balance, the water requirements for artificial supplementation have been calculated. It is estimated that the six environmentally significant pools of the South Branch will together require supplementation at 2400 m^3/day to maintain water levels at cease-to-flow levels.

A computer program has been developed to simulate the Western 5B opencut mine void water balance and to predict water levels and salinity based on different streamflow diversion options. Since July 1999, about 5 x 10^6 m^3/year of streamflow have been diverted to the Western 5B void under a rapid filling program. At this rate of streamflow diversion it is expected that the void will overflow after the winter of 2003.

Groundwater in the Collie Basin is acidic, with pH ranging between 2.6 near the underground and opencut mines to 6.3 near the southern and southeastern boundaries of the basin. The salinity of groundwater in the basin is generally less than 500 mg/L TDS. Groundwater of salinity 1000–2000 mg/L TDS occurs in areas adjacent to South Branch in the southern part of Cardiff Sub-basin. Outside the basin, groundwater salinity generally exceeds 1000 mg/L. A preliminary assessment of the effects of discharge of groundwater of low salinity on the salinity of the Collie River shows that the current discharge volumes (7 x 10^6 m^3/year) cause a reduction of about 8% in the Collie River salinity. Reduction in salinity could be as much as 15% if the groundwater levels in the basin recovered to pre-mining levels. Under increased groundwater discharge conditions, the resultant average pH of the Collie River could reduce to 6.5.

Long-term monitoring of water levels will be required for assessment of ongoing local and regional impacts of groundwater abstraction in the basin. Deeper monitoring bores may be required to develop a good understanding of the hydrogeology of deeper sediments of the basin. The results of this study will enhance management of the groundwater resources of the Collie Basin in general, and in particular ensure appropriate allocation of groundwater, and improved management of river pools and mine voids.

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9 Glossary

Abstraction	Pumping groundwater from an aquifer.
AHD	Australian Height Datum; equivalent to: Mean Sea Level (MSL) + 0.026 m; Low Water Mark Fremantle (LWMF) + 0.756 m.
Alluvium	Unconsolidated sediments transported by streams and rivers and deposited.
AMG	Australian Map Grid.
Anticline	Sedimentary strata folded in an arch.
Aquifer	A geological formation or group of ormations able to receive, store and transmit significant quantities of water.
Unconfined	A permeable bed only partially filled water and overlying a relatively impermeable layer. Its upper boundary is formed by a free watertable or phreatic level under atmospheric pressure.
Confined	A permeable bed saturated with water and lying between an upper and a lower confining layer of low permeability.
Semi-confined	A semi-confined or a leaky aquifer is saturated and bounded above by a semi-permeable layer and below by a layer that is either impermeable or semi-permeable.
Semi-unconfined	Intermediate between semi-confined and unconfined, when the upper semi-permeable layer easily transmits water.
Archaean	Period containing the oldest rocks of the Earth’s crust – older than 2.4 billion years.
Baseflow	Portion of river and streamflow coming from groundwater discharge.
Basement	Competent rock formations underneath sediments.
Bore	Small diameter well, usually drilled with machinery.
bns	Below natural surface.
Colluvium	Material transported by gravity downhill of slopes.
Confining bed	Sedimentary bed of very low hydraulic conductivity.
Conformably	Sediments deposited in a continuous sequence without a break.
Cretaceous	Final period of Mesozoic era; 65-144 million years ago.
Dewatering	Abstraction of groundwater from bores to assist in mining.
Evapotranspiration	A collective term for evaporation and transpiration.
Fault	A fracture in rocks or sediments along which there has been an observable displacement.
Flux	Flow.
Formation	A group of rocks or sediments which have certain characteristics in common, were deposited about the same geological period, and which constitute a convenient unit for description.

Hydraulic	Pertaining to groundwater motion.
Conductivity	The flow through a unit cross-sectional area of an aquifer under a unit hydraulic gradient.
Gradient	The rate of change of total head per unit distance of flow at a given poit and in a given direction.
Head	The height of the free surface of a body of water above a given subsurface point.
Lacustrine	Pertaining to, produced by, or formed in a lake.
Leach	Remove soluble matter by percolation of water.
Permian	An era of geological time; 225–280 million years ago.
Porosity	The ratio of the volume of void spaces, to the total volume of a rock matrix.
surface Potentiometric	An imaginary surface representing the total head of groundwater and defined by the level to which water will rise in a bore.
Quaternary	Relating to the most recent period in the Cainozoic era, from 2 million years to present.
Salinity	A measure of the concentration of total dissolved solids in water 0–500 mg/L, fresh 500–1500 mg/L, fresh to marginal 1500–3000 mg/L, brackish >3000 mg/L, saline.
Scarp	A line of cliffs (steep slopes) produced by faulting or by erosion.
Specific yield	The volume of water than an unconfined aquifer releases from storage per unit surface area of the aquifer per unit decline in the watertable.
Storage coefficient	The volume of water that a confined aquifer releases from storage per unit surface area of the aquifer per unit decline in the component of hydraulic head normal to that surface.
Syncline	A basin shaped fold in sedimentary strata.
Tectonic	Pertaining to forces that produce structures or features in rocks.
Tertiary	The first period of the Cainozoic era; 2–65 million years ago.
Transmissivity	The rate at which water is transmitted through a unit width of an aquifer under a unit hydraulic gradient.
Transpiration	The loss of water vapour from a plant, mainly through the leaves.
Watertable	The surface of a body of unconfined groundwater at which the pressure is equal to that of the atmosphere.
Well	Large diameter bore, usually dug by hand.

Appendix I

Summary of bore data

Bore	*Northing (m)*	*Easting (m)*	*Top of casing (m AHD)*	*Slotted (m bns)*	*Water level (m AHD)*	*TDA (mg/L)*	*pH*	*Monitoring date*
CE1-1	6300780	429980	232.550	33-45	Dry	NR	NR	18-Apr-98
CE2-1	6294425	432000	204.100	12-30	Dry	NR	NR	15-Apr-98
CX2	6301860	428560	234.120	18-30	Dry	NR	NR	18-Apr-98
CX5	6297000	430725	219.400	12-30	Dry	NR	NR	18-Apr-98
CX6	6297930	432780	232.250	12-24	Dry	NR	NR	18-Apr-98
L7	6304472	422561	190.700	12-13	186.42	NR	NR	18-Apr-98
MX5	6302091	434889	254.700	12-46	Dry	NR	NR	18-Apr-98
SE1-1	6308210	429520	225.950	12-30	Dry	NR	NR	18-Apr-98
R2104	6305451	434481	240.600	21-26	Dry	NR	NR	15-Apr-98
R2153	6306113	432928	237.600	21-25	211.85	NR	NR	18-Apr-98
CBS2A	6309750	416480	177.570	5-11	172.52	40	5.7	18-Apr-98*
CBS2B	6309750	416480	177.450	39-45	170.58	110	6.0	18-Apr-98*
CBS6	6310050	419540	206.200	8-17	199.81	740	4.5	18-Apr-98*
CBS7	6312560	424870	216.620	7-13	214.57	1160	7.7	18-Apr-98*
CBS8	6305600	418680	187.310	4-10	183.56	300	4.0	18-Apr-98*
CBS9A	6307160	419950	188.170	7-13	182.13	130	5.8	18-Apr-98*
CBS9B	6307160	419950	188.060	48-54	179.96	560	6.0	18-Apr-98*
CBS10	6308910	423920	202.140	9-15	199.38	7150	3.0	18-Apr-98*
CBS12	6304040	419730	223.000	11-19	209.59	690	6.9	18-Apr-98*
CBS13	6307510	425810	214.270	6-15	208.10	1950	3.3	18-Apr-98*
CBS14A	6308724	427662	213.670	1-7	211.47	80	5.7	18-Apr-98*
CBS14B	6308726	427661	213.700	14-20	211.10	70	5.7	18-Apr-98*
CBS14C	6308729	427656	214.040	32-35.5	210.12	170	5.8	18-Apr-98*
CBS15	6312150	428820	206.940	0-6	201.66	580	7.0	18-Apr-98*
CBS16	6301640	423160	213.270	12-21	200.24	280	5.8	18-Apr-98*
CBS17A	6302060	426230	183.870	3-10.5	Dry	600	3.6	18-Apr-98*
CBS17B	6302060	426230	184.120	39-45	157.95	110	2.6	18-Apr-98*
CBS18	6304560	424410	183.530	3-9	181.19	70	5.4	18-Apr-98*
CBS20	6305720	428920	213.530	18-24	195.45	680	3.7	18-Apr-98*
CBS21A	6308500	431625	211.970	0-5	209.50	70	5.7	18-Apr-98*
CBS21D	6308500	431690	212.750	43-49	189.60	210	5.8	18-Apr-98*
CBS23	6297680	425280	224.480	6-15	219.65	390	7.1	18-Apr-98*
CBS24	6306460	434940	234.510	28-35	Dry	450	4.5	18-Apr-98*
CBS25A	6298260	428120	187.330	1-7	183.60	1110	4.0	18-Apr-98*
CBS25B	6298260	428120	187.500	39-45	179.64	210	6.4	18-Apr-98*
CBS27	6300940	432660	217.560	0-6	214.14	490	5.0	18-Apr-98*
CBS29	6303690	435300	241.210	33-45	198.86	370	5.1	18-Apr-98*
CBS31	6296100	434580	231.180	5-11	223.92	2280	7.3	18-Apr-98*
CBS32	6300960	438450	220.570	1-9	212.63	110	6.1	18-Apr-98*
CBS34	6297080	438880	224.070	1-8	219.04	70	6.3	18-Apr-98*
CBS35	6291640	433000	198.590	2-10	194.59	70	6.1	18-Apr-98*
CBS36	6292360	435350	217.420	2-8	226.93	9350	4.5	18-Apr-98*
CBS39	6296370	436860	243.450	11-23	234.04	2460	6.7	18-Apr-98*
W677-1	6301934	425815	185.200	10-11	173.65	NR	NR	30-Apr-98
W677-2	6301934	425815	185.200	17-18	167.81	NR	NR	30-Apr-98
W677A	6301940	425806	185.000	27-33	163.18	NR	NR	30-Apr-98
W677B	6301945	425794	185.100	43-48	140.12	NR	NR	30-Apr-98
W682s	6301258	426392	186.830	21-24	172.98	NR	NR	30-Apr-98
W682d	6301258	426392	186.830	33.5-39.5	169.66	NR	NR	30-Apr-98
MR7S	6299245	437750	218.200	0.8-6.8	216.79	NR	NR	28-May-98
MR7I	6299245	437750	218.200	6.2-12.2	216.77	NR	NR	28-May-98
MR7D	6299245	437750	218.200	12.3-18.3	215.06	NR	NR	28-May-98

NR: Not Recorded; *Only water level recorded on this date, salinity and pH recorded in July-August 1989

Appendix I Summary of bore data (continued)

Bore	*Northing (m)*	*Easting (m)*	*Top of casing (m AHD)*	*Slotted (m bns)*	*Water level (m AHD)*	*TDA (mg/L)*	*pH*	*Monitoring date*
MR18S(b)	6301265	437120	228.700	12-18	Dry	NR	NR	28-May-98
MR18S(c)	6301265	437120	228.700	18-24	207.23	NR	NR	28-May-98
MR22S	6300328	437485	215.400	6-12	205.38	NR	NR	28-May-98
MR22I	6300327	437485	215.450	12-18	205.49	NR	NR	28-May-98
MR22D	6300326	437484	215.580	18-24	Blocked	NR	NR	28-May-98
MR23S	6300802	437457	214.920	6-12	205.03	NR	NR	28-May-98
MR23I	6300800	437456	214.870	12-18	205.59	NR	NR	28-May-98
MR23D	6300801	437456	214.900	18-24	205.68	NR	NR	28-May-98
MR24S	6299216	437335	237.160	18-24	Dry	NR	NR	28-May-98
MR24I	6299215	437334	237.190	24-30	208.30	NR	NR	28-May-98
MR24D	6299213	437333	237.130	30-36	203.17	NR	NR	28-May-98
CR1	6302905	437335	213.100	6.1-12.1	202.15	NR	NR	29-May-98
CR2S	6303080	437320	212.500	6-12	Dry	NR	NR	29-May-98
CR2I	6303080	437320	213.030	11-18	200.23	NR	NR	29-May-98
CR2D	6303080	437320	212.700	17-24	199.67	NR	NR	29-May-98
CR3S	6303395	437120	212.600	6-12	198.63	NR	NR	29-May-98
CR3I	6303395	437120	212.340	12-18	Dry	NR	NR	29-May-98
CR3D	6303395	437120	211.850	18-24	Dry	NR	NR	29-May-98
CR4S	6303695	436940	213.200	6-12	203.91	NR	NR	29-May-98
CR4I	6303695	436940	212.960	12-18	203.84	NR	NR	29-May-98
CR4D	6303695	436940	21.850	18-24	201.63	NR	NR	29-May-98
CR10S(a)	6303725	436740	224.400	16-22	205.32	NR	NR	29-May-98
CR10S(b)	6303725	436740	224.200	22-28	204.76	NR	NR	29-May-98
CR10I	6303725	436740	224.300	28-34	196.93	NR	NR	29-May-98
CR15SA	6302858	437075	215.440	6-12	204.53	NR	NR	29-May-98
CT15B	6302857	437075	215.220	12-18	Dry	NR	NR	29-May-98
CR15C	6302856	437074	215.130	18-24	191.90	NR	NR	29-May-98
MR1	6299020	437160	237.000	6-12	230.70	NR	NR	28-May-98
MR3	6298720	437540	236.900	8.3-14.3	225.85	NR	NR	28-May-98
MEW07a	6309331	427099	221.350	12.5-18.5	210.87	NR	NR	07-Apr-98
MEW07b	6309331	427099	221.350	62.6-68.6	214.07	NR	NR	07-Apr-98
ME1a	6306804	429825	213.950	24-28	189.21	NR	NR	07-Apr-98
ME1b	6306804	429828	213.950	46.5-52.5	182.68	NR	NR	07-Apr-98
ME6/A	6307482	429761	213.450	11-14.5	Not avail.	NR	NR	
ME6/B	6307481	429761	213.450	27-32.5	180.34	NR	NR	07-Apr-98
ME6/C	6307480	429761	213.450	50-56	183.19	NR	NR	07-Apr-98
ME8/A	6307539	430298	221.400	24-31	193.19	NR	NR	07-Apr-98
ME8/B	6307540	430297	221.400	37-40	184.68	NR	NR	07-Apr-98
ME8/C	6307541	430295	221.400	50-55	172.92	NR	NR	07-Apr-98
ME8/D	6307542	430294	221.400	66-71	172.50	NR	NR	07-Apr-98
MER1/A	6306271	430070	228.428	4-10	218.92	NR	NR	08-Apr-98
MER1/B	6306273	430071	228.371	34-38	198.52	NR	NR	08-Apr-98
MER1/D	6306275	430072	228.467	42.5-43.5	201.54	NR	NR	08-Apr-98
MER2/A	6306064	431196	230.228	32.5-38.5	209.01	NR	NR	08-Apr-98
MER2/B	6306066	431195	230.239	43-46.5	188.92	NR	NR	08-Apr-98
MER2/C	6306067	431195	230.321	50-56	189.41	NR	NR	08-Apr-98
MER2/D	6306068	431194	230.472	78-84	180.19	NR	NR	08-Apr-98
MER3/A	6305489	430363	227.005	9-15	217.62	NR	NR	08-Apr-98
MER3/B	6305490	430362	227.020	18-22	216.51	NR	NR	08-Apr-98
MER4/A	6305820	431673	227.713	13-19	211.09	NR	NR	08-Apr-98
MER4/B	6305821	431686	228.097	41-47	200.28	NR	NR	08-Apr-98
MER4/C	6305819	431686	228.010	57-63	186.13	NR	NR	08-Apr-98
MER4/D	6305818	431685	227.936	85-91	178.22	NR	NR	08-Apr-98
MER4/E	6305817	431685	227.851	111-114	179.05	NR	NR	08-Apr-98
MER5/A	6308390	430794	222.028	39-41	187.54	NR	NR	08-Apr-98
MER5/C	6308388	430792	222.056	59-60	185.67	NR	NR	08-Apr-98

Appendix I Summary of bore data (continued)

Bore	Northing (m)	Easting (m)	Top of casing (m AHD)	Slotted (m bns)	Water level (m AHD)	TDA (mg/L)	pH	Monitoring date
MER6/A	6309247	430439	222.721	12-24	198.92	NR	NR	08-Apr-98
MER6/B	6309249	430438	222.792	29-41	189.08	NR	NR	08-Apr-98
MER6/C	6309251	430438	222.801	50-60	191.62	NR	NR	08-Apr-98
MER7/A	6308076	431606	211.790	18-30	204.46	NR	NR	08-Apr-98
MER7/B	6308077	431608	211.652	76-85	186.15	NR	NR	08-Apr-98
MER7/C	6308079	431611	211.664	99-101	185.46	NR	NR	08-Apr-98
MER7/D	6308080	431613	211.668	109-115	185.04	NR	NR	08-Apr-98
MER8/A	6307624	431590	213.037	21-27	203.39	NR	NR	08-Apr-98
MER8/B	6307624	431592	213.037	35-41	191.54	NR	NR	08-Apr-98
MER8/C	6307624	431594	213.060	52-64	185.30	NR	NR	08-Apr-98
MER8/D	6307624	431598	213.062	82.9-83.9	184.92	NR	NR	08-Apr-98
MER9/A	6305977	432495	229.546	23-29	201.07	NR	NR	08-Apr-98
MER9/B	6305977	432497	229.611	56-62	184.17	NR	NR	08-Apr-98
MER9/C	6305977	432498	229.599	97-99	182.28	NR	NR	08-Apr-98
MER9/D	6305977	432500	229.550	109-119	181.77	NR	NR	08-Apr-98
MER10/A	6307193	432405	217.618	14-20	204.68	NR	NR	08-Apr-98
MER10/B	6307194	432405	217.567	36-48	202.45	NR	NR	08-Apr-98
MER10/C	6307196	432405	217.644	111-123	184.25	NR	NR	08-Apr-98
MER10/D	6307198	432404	217.647	133-139	183.25	NR	NR	08-Apr-98
MER11/A	6305861	432056	237.370	8-14	223.65	NR	NR	08-Apr-98
MER11/B	6305862	432055	237.410	33-39	198.76	NR	NR	08-Apr-98
CRM-01/98	6311289	415932	186.666	7.2-10.2	183.50	130	5.7	08-Jun-98
CRM-03/98	6311049	424078	190.656	11.4-14.4	185.99	3480	5.7	02-Jun-98
CRM-04/98	6311311	426196	225.822	11.3-14.3	214.26	630	4.7	29-May-98
CRM-05/98	6310634	414904	187.274	11.2-14.2	179.45	820	3.9	08-Jun-98
CRM-06/98	6310872	417531	195.294	11-14	189.04	660	5.4	02-Jun-98
CRM-07/98	6310154	423904	229.349	20.5-23.5	213.92	6080	5.6	08-Jun-98
CRM-08/98	6310661	425080	214.161	8.3-11.3	205.22	330	4.9	02-Jun-98
CRM-09/98	6310182	427497	228.127	15.6-18.6	216.60	1610	4.7	29-May-98
CRM-10/98	6310231	430082	228.559	14.9-20.9	213.79	420	5.2	11-May-98
CRM-11/98	6309523	418326	193.797	10-13	185.80	40	5.3	05-Jun-98
CRM-12/98	6309736	421658	207.980	17.9-20.9	192.94	580	4.8	09-Jun-98
CRM-13/98	6309301	425048	212.984	10-13	206.88	100	5.5	02-Jun-98
CRM-15/98	6309776	430964	250.200	48.8-56.8	200.97	360	4.8	04-Jun-98
CRM-17/98	6309220	415226	172.049	14.7-17.7	170.90	70	5.3	12-May-98
CRM-19/98	6308659	418074	230.509	53.8-56.8	179.61	380	5.6	12-May-98
CRM-20/98	6309053	421201	187.329	8.6-11.6	184.45	300	4.1	10-Jun-98
CRM-21/98	6309004	426624	241.933	38.7-41.7	209.01	230	4.9	11-May-98
CRM-22/98	6308004	417098	223.118	43.7-47.7	180.70	180	5.2	12-May-98
CRM-23/98	6308023	419424	212.907	35.7-38.7	180.16	70	5.5	08-Jun-98
CRM-24/98	6308264	422472	189.134	7.5-10.5	183.53	240	5.3	02-Jun-98
CRM-25/98	6308178	427228	243.568	35.7-38.7	209.49	300	4.3	12-May-98
CRM-27/98	6307059	418294	187.824	7.6-10.6	181.27	130	6.6	09-Jun-98
CRM-28/98	6307483	421108	181.063	5.5-8.5	179.52	230	6.0	05-Jun-98
CRM-30/98	6307322	428138	220.815	14.7-17.7	209.52	230	4.4	11-May-98
CRM-31/98	6306939	433749	233.602	22-30	213.16	2100	3.8	04-Jun-98
CRM-32/98	6306533	421710	189.818	9.3-12.3	183.37	170	5.4	18-May-98
CRM-33/98	6306913	423025	193.467	10.3-13.3	187.27	180	6.0	05-Jun-98
CRM-34/98	6306403	424708	228.891	41.7-44.7	189.07	580	5.2	25-May-98
CRM-35/98	6306545	427188	212.923	17.5-20.5	198.72	150	5.4	22-May-98
CRM-37/98	6305819	420992	179.724	5-8	178.98	410	6.3	14-May-98
CRM-38/98	6305533	423708	199.169	26.7-29.7	185.17	140	5.5	09-Jun-98
CRM-39/98	6305040	419939	200.438	9.5-12.5	195.45	160	5.1	14-May-98
CRM-40/98	6305242	422005	180.142	5.5-8.5	176.88	150	5.2	13-May-98
CRM-41/98	6305304	425957	218.317	32.7-35.7	188.11	210	5.6	25-May-98
CRM-42/98	6305193	427689	196.589	4.7-7.7	191.77	400	5.3	26-May-98

Appendix I Summary of bore data (continued)

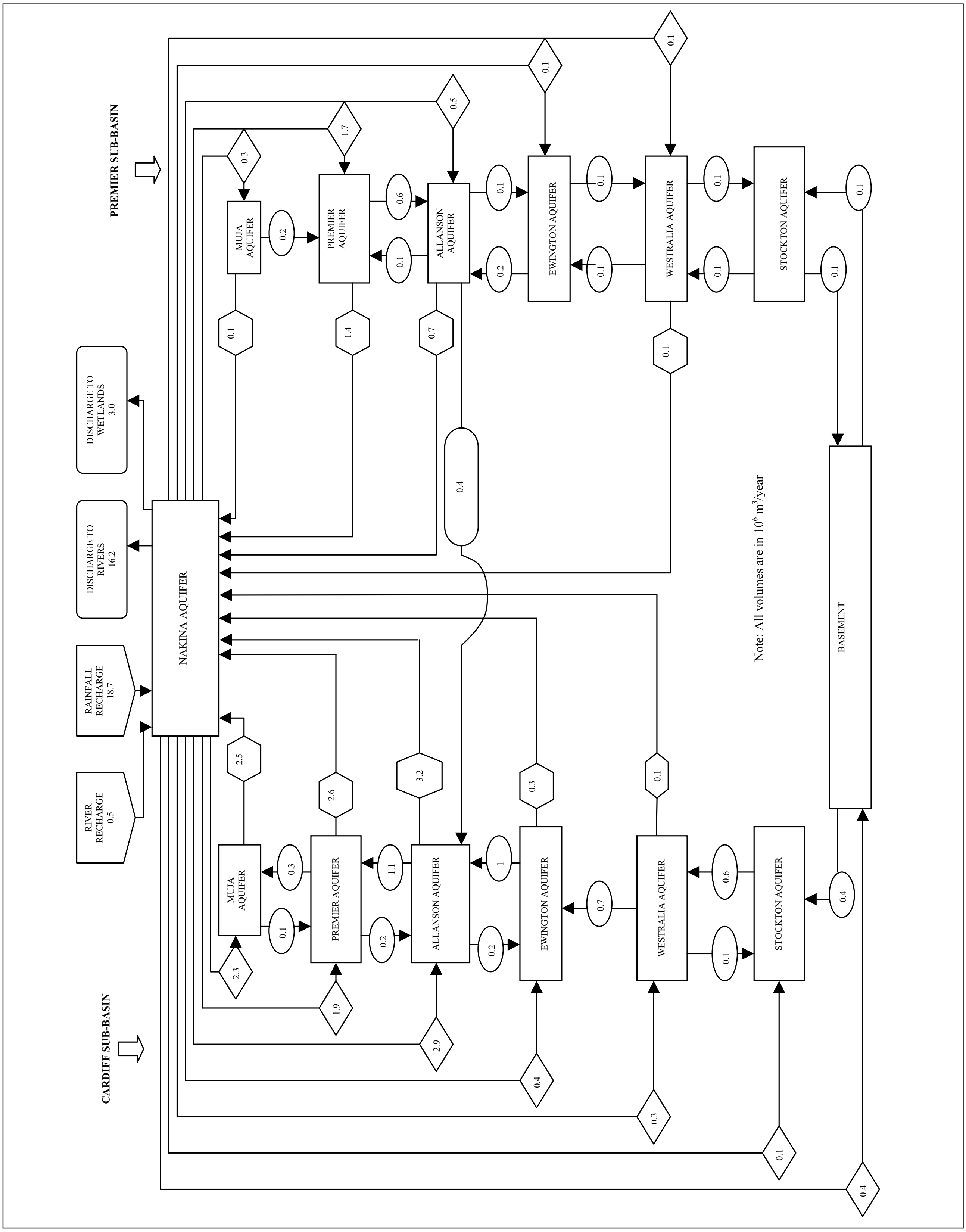
Bore	*Northing (m)*	*Easting (m)*	*Top of casing (m AHD)*	*Slotted (m bns)*	*Water level (m AHD)*	*TDA (mg/L)*	*pH*	*Monitoring date*
CRM-43/98	6304403	421159	208.863	35.4-38.4	180.05	290	5.0	14-May-98
CRM-44/98	6304263	426843	188.506	9.1-12.1	184.80	160	5.5	25-May-98
CRM-45/98	6304764	436657	210.906	7.3-15.3	205.15	4200	6.3	03-Jun-98
CRM-46/98	6304678	437743	216.159	9.4-17.4	212.72	17300	4.0	03-Jun-98
CRM-47/98	6303718	424084	200.769	41.7-44.7	160.03	260	5.4	09-Jun-98
CRM-48/98	6303731	425763	194.806	23.7-26.7	177.06	370	5.5	21-May-98
CRM-50/98	6303995	428060	190.401	7.4-10.4	187.27	660	5.2	21-May-98
CRM-51/98	6303699	429664	196.218	6.5-9.5	192.16	240	5.9	26-May-98
CRM-52/98	6303335	422408	200.209	8.8-11.8	192.53	260	5.5	14-May-98
CRM-53/98	6302774	421560	211.349	9.3-12.3	205.10	80	4.8	14-May-98
CRM-54/98	6303005	427499	221.745	37.7-41.7	184.85	390	4.2	21-May-98
CRM-55/98	6302895	429205	208.033	20.7-23.7	193.27	130	5.5	26-May-98
CRM-56/98	6303367	430674	199.005	9.1-12.1	192.36	1270	5.7	26-May-98
CRM-58/98	6303320	438370	215.754	5.9-13.9	211.58	4720	5.6	03-Jun-98
CRM-59/98	6302813	432613	211.117	11.8-17.8	206.55	970	6.5	04-Jun-98
CRM-60/98	6301627	424488	208.895	23.7-26.7	187.80	130	5.0	09-Jun-98
CRM-61/98	6301093	427178	184.252	14.7-20.7	169.22	1620	4.2	20-May-98
CRM-62/98	6301647	430280	205.093	12-15	192.24	370	5.8	26-May-98
CRM-63/98	6300713	425812	197.781	11.7-14.7	188.98	380	4.5	18-May-98
CRM-65/98	6301534	432675	218.682	11.7-14.7	211.44	1020	4.9	28-May-98
CRM-66/98	6300324	423310	222.493	14.7-17.7	215.61	600	5.3	18-May-98
CRM-67/98	6300088	424577	202.469	29.7-32.7	181.10	470	5.5	18-May-98
CRM-68/98	6300110	427547	184.476	6.5-9.5	179.95	1680	3.9	20-May-98
CRM-69/98	6300168	439065	232.090	21.5-29.5	217.29	300	5.7	03-Jun-98
CRM-71/98	6299497	427938	186.213	8.3-11.3	179.96	1170	6.2	19-May-98
CRM-72/98	6299228	429051	195.954	26.7-32.7	165.98	140	5.4	20-May-98
CRM-73/98	6298925	425619	212.604	20.8-23.8	200.23	370	5.5	19-May-98
CRM-74/98	6299054	430472	209.602	39.7-47.7	175.56	210	5.4	28-May-98
CRM-75/98	6298905	427039	195.980	9.4-12.4	190.42	110	5.9	19-May-98
CRM-76/98	6298725	431869	208.189	20.6-26.6	182.69	160	6.1	28-May-98
CRM-77/98	6298653	439615	236.527	14.2-17.2	222.20	2390	6.2	03-Jun-98
CRM-78/98	6298041	430970	206.421	25.2-28.2	182.47	220	5.4	27-Aug-98
CRM-79/98	6296846	427597	205.006	16.3-19.3	195.57	1760	4.1	21-May-98
CRM-80/98	6297201	429711	194.361	8.7-11.7	182.74	1240	5.7	20-May-98
CRM-81/98	6296697	432477	208.957	15.8-23.8	Dry			03-Apr-98
CRM-82/98	6295872	429204	198.758	14.5-20.5	182.73	480	6.2	20-May-98
CRM-83/98	6295428	431660	224.897	37.7-38.7	196.61	240	4.8	27-May-98
CRM-84/98	6295683	432900	230.870	53.7-62.7	176.44	250	5.2	28-May-98
CRM-85/98	6295188	428163	203.649	8.7-11.7	196.60	420	5.6	19-May-98
CRM-86/98	6294373	430480	198.438	6.9-14.9	189.88	560	4.5	27-May-98
CRM-87/98	6294579	433575	236.193	72.3-75.3	167.92	740	6.3	09-Jun-98
CRM-89/98	6293087	431650	194.404	9.9-12.9	186.73	640	5.6	27-May-98
CRM-90/98	6293066	433018	204.459	24-27	184.81	647	6.2	27-Aug-98
2257a	6306451	434096	251.700	35.6-41.6	212.95	NR	NR	29-Apr-98
2257b	6306451	434096	251.700	51.2-55.7	207.47	NR	NR	29-Apr-98
2257c	6306451	434096	251.700	67.2-69.7	209.95	NR	NR	29-Apr-98
2257d	6306451	434096	251.700	81-85	203.29	NR	NR	29-Apr-98
2299a	6305744	435205	221.350	33.5-39.5	204.70	NR	NR	29-Apr-98
2299b	6305744	435205	221.350	52-58	196.66	NR	NR	29-Apr-98
2522a	6303079	434928	239.800	22-34	210.09	NR	NR	30-Apr-98
2522b	6303079	434928	239.800	38-46	205.59	NR	NR	30-Apr-98
2522c	6303079	434928	239.800	50-55	204.46	NR	NR	30-Apr-98
2522d	6303079	434928	239.800	60-95	198.57	NR	NR	30-Apr-98
2522e	6303079	434928	239.800	105-141	197.06	NR	NR	30-Apr-98
2524a	6303438	435439	250.200	31-55	198.91	NR	NR	30-Apr-98
2524b	6303438	435439	250.200	92-96	197.43	NR	NR	30-Apr-98

Appendix I Summary of bore data (continued)

Bore	*Northing (m)*	*Easting (m)*	*Top of casing (m AHD)*	*Slotted (m bns)*	*Water level (m AHD)*	*TDA (mg/L)*	*pH*	*Monitoring date*
2524c	6303438	435439	250.200	122-139	187.39	NR	NR	30-Apr-98
2524d	6303438	435439	250.200	165-177	195.23	NR	NR	30-Apr-98
2524e	6303438	435439	250.200	188-191	193.27	NR	NR	30-Apr-98
2530a	6304669	435216	223.730	9.7-15.7	214.54	NR	NR	29-Apr-98
2530b	6304669	435216	223.730	40.8-46.8	197.63	NR	NR	29-Apr-98
2531a	6304403	435628	239.090	10-12	Dry	NR	NR	09-Apr-98
2531b	6304403	435628	239.090	32.2-38.2	200.47	NR	NR	29-Apr-98
2532a	6305018	435488	218.340	11-15	203.14	NR	NR	29-Apr-98
2532b	6305018	435488	218.340	25.5-31.5	196.53	NR	NR	29-Apr-98
2533a	6305095	435636	222.270	9-11	Dry	NR	NR	29-Apr-98
2533b	6305095	435636	222.270	25.4-31.4	199.71	NR	NR	29-Apr-98
2534a	6305639	435297	218.250	7-9	210.52	NR	NR	29-Apr-98
2534b	6305639	435297	218.250	22.9-28.9	205.64	NR	NR	29-Apr-98
2535a	6307109	434247	223.970	7-8	215.33	NR	NR	29-Apr-98
2535b	6307109	434247	223.970	12-18	211.64	NR	NR	29-Apr-98
2535c	6307109	434247	223.970	28-40	199.05	NR	NR	29-Apr-98
2536a	6307866	432879	217.890	9.3-11.3	204.94	NR	NR	29-Apr-98
2536b	6307866	432879	217.890	28.8-40.8	Dry	NR	NR	29-Apr-98
2538a	6308395	432512	213.670	6.5-7.5	Dry	NR	NR	29-Apr-98
2538b	6308395	432512	213.670	17.7-29.7	205.20	NR	NR	29-Apr-98
2539a	6307082	432363	219.010	13.8-19.8	206.60	NR	NR	29-Apr-98
2539b	6307082	432363	219.010	28-40	203.09	NR	NR	29-Apr-98
2540a	6306538	432658	223.230	16-28	201.30	NR	NR	29-Apr-98
2540b	6306538	432658	223.230	40.7-46.7	197.55	NR	NR	29-Apr-98
2542a	6305999	432370	230.150	11-20	Dry	NR	NR	30-Apr-98
2542b	6305999	432370	230.150	28-30	202.66	NR	NR	30-Apr-98
2543a	6305910	432715	233.830	20-32	203.99	NR	NR	30-Apr-98
2543b	6305910	432715	233.830	41-46	191.32	NR	NR	30-Apr-98
2544a	6305766	432608	237.070	13-25	Dry	NR	NR	30-Apr-98
2544b	6305766	432608	237.070	35-41	197.49	NR	NR	30-Apr-98
2547	6305645	431997	226.490	11-20	208.66	NR	NR	30-Apr-98
2548a	6305371	431577	223.020	17-23	202.98	NR	NR	30-Apr-98
2548b	6305371	431577	223.020	38.9-44.9	180.67	NR	NR	30-Apr-98
2549a	6304958	433165	229.000	20-26	209.65	NR	NR	28-Apr-98
2549b	6304958	433165	229.000	33-36	197.21	NR	NR	28-Apr-98
2549c	6304958	433165	229.000	52-63	172.65	NR	NR	28-Apr-98
2549d	6304958	433165	229.000	80-98	180.03	NR	NR	28-Apr-98
2549e	6304958	433165	229.000	113-125	182.04	NR	NR	28-Apr-98
ACARP1	6310413	425478	199.377	5.1-7.1	197.32	NR	NR	09-Jul-98
ACARP2	6310442	425349	201.129	5.2-7.2	197.55	NR	NR	09-Jul-98
ACARP3	6310320	425480	201.559	5.6-7.6	198.07	NR	NR	09-Jul-98
ACARP4	6310258	425454	202.319	5.6-8.3	199.40	NR	NR	09-Jul-98
ACARP5	6310161	425584	199.346	6.5-8.5	199.35	NR	NR	09-Jul-98
ACARP7	6310195	425274	213.063	5.2-7.2	209.87	NR	NR	09-Jul-98
ACARP8	6310379	425169	202.949	4.4-6.4	198.75	NR	NR	09-Jul-98
ACARP9	6311027	425293	206.531	4.6-6.6	200.41	NR	NR	09-Jul-98
ACARP10	6310534	425279	197.214	3.6-5.6	196.12	NR	NR	09-Jul-98
WP1	6299922	427057	188.761	7.4-10.4	180.18	NR	NR	01-Aug-99
WP2	6300078	427263	186.886	6-9	180.10	NR	NR	01-Aug-99
WP3	6300253	427520	184.173	3.6-6.8	179.32	NR	NR	01-Aug-99
WP4	6300388	427544	188.287	7.6-10.6	181.24	NR	NR	01-Aug-99
LP1	6299156	427554	188.991	3.3-6.3	184.51	NR	NR	01-Aug-99
LP2	6299188	427786	187.036	3-6	183.11	NR	NR	01-Aug-99

Appendix II

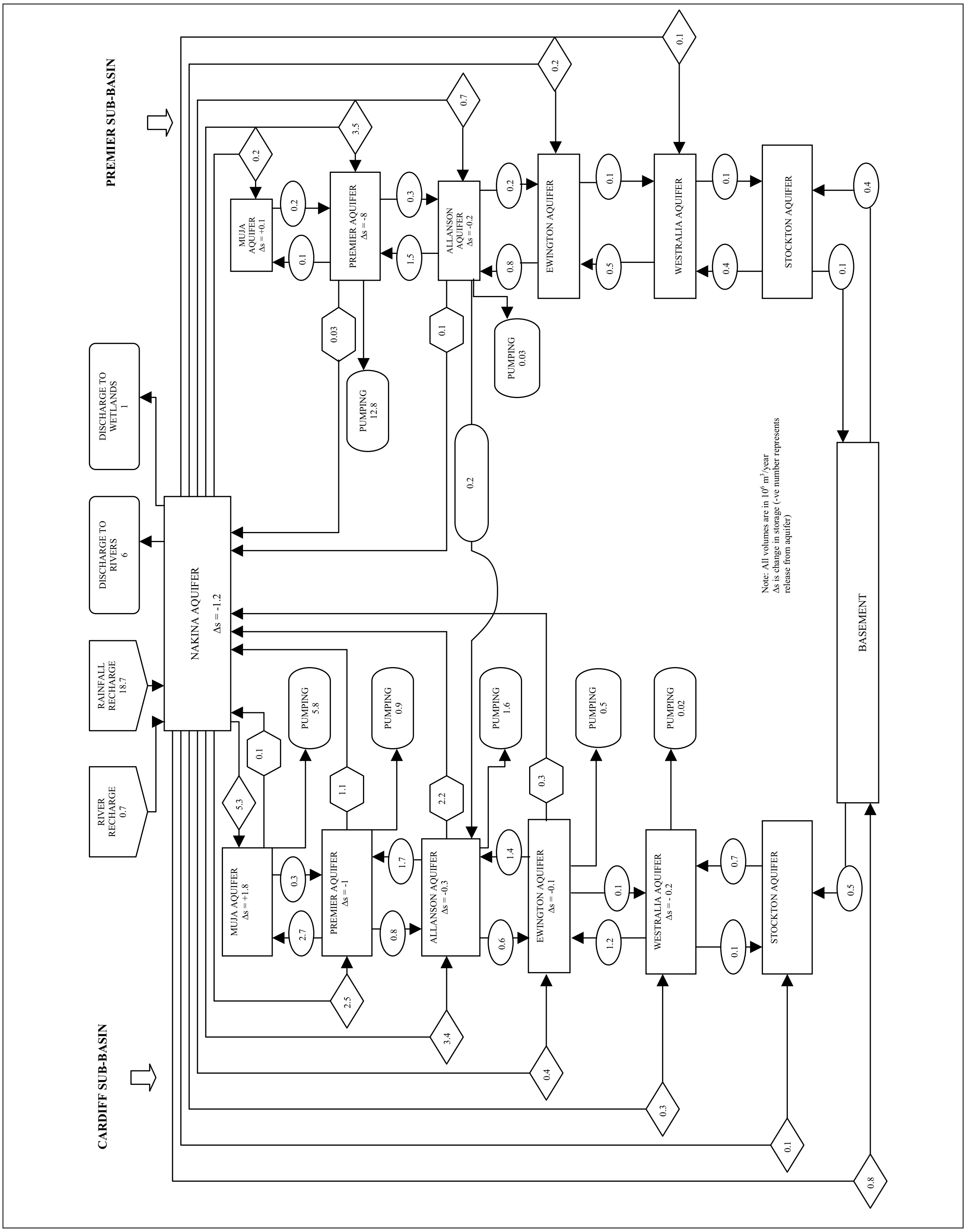
Groundwater balance of the Collie Basin under pre-mining steady state conditions derived from the model



Note: All volumes are in 10^6 m^3/year

Appendix III

Groundwater balance of the Collie Basin for 1999 derived from the model



Appendix IV

Western 5B opencut mine void water balances

Western 5B void water balances – Option 1

(no streamflow diversion)

Year	*GW inflow m^3*	*Runoff m^3*	*Evap. m^3*	*Rainfall m^3*	*Stream flow m^3*	*Leakage m^3*	*Water level m AHD*	*TDS mg/L*	*Overflow m^3*
1997*	695935	240295	-54875	37051	0	0	128.88	613	0
1998	1762265	219523	-198472	115193	0	0	141.87	679	0
1999	2323798	189588	-354393	195020	0	0	151.24	710	0
2000	2495354	162388	-503510	267554	0	0	158.21	731	0
2001	2422997	139120	-635640	329600	0	0	163.46	749	0
2002	2225873	119907	-747546	380836	0	0	167.44	765	0
2003	1982326	104395	-839590	422203	0	0	170.45	781	0
2004	1737504	92058	-913804	455099	0	0	172.75	797	0
2005	1514169	82352	-972806	480983	0	0	174.50	814	0
2006	1321463	74772	-1019240	501195	0	0	175.83	830	0
2007	1160934	68885	-1055514	516894	0	0	176.85	848	0
2008	1030357	64333	-1083692	529033	0	0	177.63	866	0
2009	925869	60823	-1105491	538393	0	0	178.22	884	0
2010	843229	58123	-1122306	545593	0	0	178.67	903	0
2011	778436	56050	-1135241	551122	0	0	179.02	922	0
2012	727961	54460	-1145173	555361	0	0	179.28	942	0
2013	688811	53243	-1152787	558607	0	0	179.48	961	0
2014	658558	52312	-1158617	561090	0	0	179.64	982	0
2015	635237	51600	-1163076	562987	0	0	179.75	1002	0
2016	617303	51057	-1166481	564435	0	0	179.84	1023	0
2017	603523	50643	-1169080	565540	0	0	179.91	1044	0
2018	592950	50327	-1171060	566382	0	0	179.96	1064	0
2019	584834	50087	-1172566	567022	0	0	180.00	1086	0
2020	578623	49905	-1173711	567508	0	0	180.03	1107	0
2021	573877	49768	-1174575	567874	0	0	180.05	1128	0
2022	570232	49664	-1175228	568152	0	0	180.07	1149	0
2023	567429	49585	-1175721	568362	0	0	180.08	1171	0
2024	565271	49526	-1176093	568519	0	0	180.09	1192	0
2025	563605	49482	-1176369	568637	0	0	180.10	1213	0
2026	562343	49450	-1176571	568722	0	0	180.11	1235	0
2027	561383	49427	-1176716	568782	0	0	180.11	1256	0
2028	560633	49411	-1176820	568826	0	0	180.11	1278	0
2029	560042	49399	-1176893	568858	0	0	180.11	1299	0
2030	559607	49392	-1176939	568876	0	0	180.11	1321	0
2031	559273	49388	-1176964	568886	0	0	180.11	1343	0
2032	559012	49386	-1176975	568891	0	0	180.11	1364	0
2033	558800	49386	-1176977	568892	0	0	180.11	1386	0
2034	558636	49387	-1176970	568888	0	0	180.11	1407	0
2035	558497	49389	-1176959	568883	0	0	180.11	1429	0
2036	558383	49392	-1176942	568877	0	0	180.11	1450	0
2037	558290	49395	-1176921	568867	0	0	180.11	1472	0
2038	558211	49399	-1176899	568857	0	0	180.11	1494	0
2039	558148	49403	-1176873	568846	0	0	180.11	1515	0
2040	558097	49408	-1176845	568833	0	0	180.11	1537	0
2041	558052	49413	-1176815	568821	0	0	180.11	1558	0
2042	558012	49418	-1176784	568807	0	0	180.11	1580	0
2043	557975	49423	-1176754	568794	0	0	180.11	1601	0

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* From March 1997

Western 5B void water balances – Option 1 (continued)

Year	GW inflow m^3	Runoff m^3	Evap. m^3	Rainfall m^3	Stream flow m^3	Leakage m^3	Water level m AHD	TDS mg/L	Overflow m^3
2044	557937	49428	-1176723	568781	0	0	180.11	1623	0
2045	557899	49433	-1176692	568767	0	0	180.11	1645	0
2046	557864	49438	-1176661	568754	0	0	180.10	1666	0
2047	557832	49443	-1176629	568740	0	0	180.10	1688	0
2048	557802	49448	-1176597	568726	0	0	180.10	1709	0
2049	557771	49454	-1176565	568712	0	0	180.10	1731	0
2050	557742	49459	-1176533	568698	0	0	180.10	1753	0
2051	557712	49464	-1176500	568684	0	0	180.10	1774	0
2052	557682	49469	-1176467	568670	0	0	180.10	1796	0
2053	557652	49475	-1176435	568656	0	0	180.10	1817	0
2054	557624	49480	-1176402	568642	0	0	180.10	1839	0
2055	557597	49485	-1176370	568628	0	0	180.10	1861	0
2056	557570	49491	-1176337	568613	0	0	180.10	1882	0
2057	557542	49496	-1176304	568599	0	0	180.09	1904	0
2058	557515	49501	-1176271	568585	0	0	180.09	1925	0
2059	557488	49506	-1176239	568571	0	0	180.09	1947	0
2060	557461	49512	-1176206	568557	0	0	180.09	1969	0
2061	557433	49517	-1176173	568542	0	0	180.09	1990	0
2062	557408	49523	-1176140	568528	0	0	180.09	2012	0
2063	557384	49528	-1176107	568513	0	0	180.09	2033	0
2064	557359	49533	-1176075	568499	0	0	180.09	2055	0
2065	557334	49539	-1176041	568485	0	0	180.09	2077	0
2066	557307	49544	-1176008	568470	0	0	180.09	2098	0
2067	557282	49550	-1175975	568456	0	0	180.08	2120	0
2068	557258	49555	-1175941	568441	0	0	180.08	2141	0
2069	557236	49560	-1175908	568426	0	0	180.08	2163	0
2070	557211	49566	-1175875	568412	0	0	180.08	2185	0
2071	557187	49571	-1175841	568398	0	0	180.08	2206	0
2072	557162	49577	-1175809	568384	0	0	180.08	2228	0
2073	557138	49582	-1175775	568369	0	0	180.08	2249	0
2074	557113	49588	-1175741	568355	0	0	180.08	2271	0
2075	557089	49593	-1175708	568340	0	0	180.08	2293	0
2076	557064	49598	-1175675	568326	0	0	180.07	2314	0
2077	557040	49604	-1175642	568311	0	0	180.07	2336	0
2078	557014	49609	-1175609	568297	0	0	180.07	2358	0
2079	556987	49614	-1175576	568283	0	0	180.07	2379	0
2080	556960	49620	-1175543	568269	0	0	180.07	2401	0
2081	556936	49625	-1175510	568254	0	0	180.07	2422	0
2082	556911	49631	-1175477	568240	0	0	180.07	2444	0
2083	556886	49636	-1175443	568225	0	0	180.07	2466	0
2084	556865	49642	-1175410	568211	0	0	180.07	2487	0
2085	556842	49647	-1175376	568196	0	0	180.07	2509	0
2086	556820	49652	-1175342	568182	0	0	180.06	2530	0
2087	556796	49658	-1175309	568167	0	0	180.06	2552	0
2088	556771	49663	-1175275	568152	0	0	180.06	2574	0
2089	556747	49669	-1175242	568138	0	0	180.06	2595	0
2090	556722	49674	-1175209	568124	0	0	180.06	2617	0
2091	556698	49680	-1175176	568109	0	0	180.06	2639	0
2092	556673	49685	-1175143	568095	0	0	180.06	2660	0
2093	556649	49690	-1175110	568080	0	0	180.06	2682	0
2094	556624	49696	-1175076	568066	0	0	180.06	2703	0
2095	556600	49701	-1175043	568051	0	0	180.06	2725	0
2096	556577	49707	-1175009	568037	0	0	180.05	2747	0

Western 5B void water balances – Option 2

(streamflow diversion: 5 x 10^6 m^3/year for 100 years)

Year	*GW inflow* m^3	*Runoff* m^3	*Evap.* m^3	*Rainfall* m^3	*Stream flow* m^3	*Leakage* m^3	*Water level* *m AHD*	*TDS* *mg/L*	*Overflow* m^3
1997*	695935	240295	-54875	37051	0	0	128.88	613	0
1998	1762265	219523	-198472	115193	0	0	141.87	679	0
1999	2305812	170276	-467784	246520	4999998	0	163.98	959	0
2000	1864041	103253	-850871	425247	4999998	0	175.53	1027	0
2001	745555	57329	-1130429	547710	4999998	-2277	182.68	1082	0
2002	74492	25169	-1333159	633472	4999998	-419907	187.40	1132	0
2003	0	7035	-1457569	688023	4999998	-1077825	189.10	1173	1615755
2004	0	2006	-1493866	703640	4999998	-1288816	189.10	1206	2924570
2005	0	2007	-1493860	703637	4999998	-1289132	189.10	1232	2924288
2006	0	2008	-1493855	703635	4999998	-1289386	189.10	1253	2924057
2007	0	2008	-1493851	703634	4999998	-1289593	189.10	1271	2923890
2008	0	2009	-1493847	703632	4999998	-1289761	189.10	1285	2923717
2009	0	2009	-1493846	703631	4999998	-1289911	189.10	1298	2923572
2010	0	2009	-1493844	703630	4999998	-1290035	189.10	1308	2923449
2011	0	2010	-1493842	703629	4999998	-1290141	189.10	1318	2923334
2012	0	2010	-1493841	703628	4999998	-1290233	189.10	1326	2923247
2013	0	2010	-1493840	703627	4999998	-1290315	189.10	1333	2923139
2014	0	2010	-1493839	703627	4999998	-1290384	189.10	1339	2923066
2015	0	2010	-1493838	703626	4999998	-1290447	189.10	1345	2922994
2016	0	2010	-1493837	703626	4999998	-1290504	189.10	1350	2922943
2017	0	2011	-1493836	703625	4999998	-1290554	189.10	1354	2922871
2018	0	2011	-1493836	703625	4999998	-1290601	189.10	1358	2922842
2019	0	2011	-1493835	703625	4999998	-1290641	189.10	1362	2922799
2020	0	2011	-1493834	703624	4999998	-1290675	189.10	1365	2922741
2021	0	2011	-1493834	703624	4999998	-1290710	189.10	1369	2922727
2022	0	2011	-1493834	703624	4999998	-1290743	189.10	1371	2922698
2023	0	2011	-1493834	703623	4999998	-1290771	189.10	1374	2922669
2024	0	2011	-1493833	703623	4999998	-1290796	189.10	1376	2922625
2025	0	2011	-1493832	703623	4999998	-1290820	189.10	1379	2922611
2026	0	2011	-1493831	703622	4999998	-1290837	189.10	1381	2922568
2027	0	2011	-1493830	703622	4999998	-1290859	189.10	1382	2922553
2028	0	2011	-1493830	703622	4999998	-1290878	189.10	1384	2922546
2029	0	2011	-1493830	703622	4999998	-1290896	189.10	1386	2922517
2030	0	2011	-1493830	703622	4999998	-1290913	189.10	1387	2922437
2031	0	2012	-1493829	703622	4999998	-1290925	189.10	1389	2922316
2032	0	2012	-1493829	703622	4999998	-1290943	189.10	1390	2922265
2033	0	2012	-1493829	703621	4999998	-1290955	189.10	1391	2922251
2034	0	2012	-1493829	703621	4999998	-1290969	189.10	1393	2922251
2035	0	2012	-1493829	703621	4999998	-1290983	189.10	1394	2922243
2036	0	2012	-1493828	703621	4999998	-1290993	189.10	1395	2922222
2037	0	2012	-1493828	703621	4999998	-1291002	189.10	1396	2922200
2038	0	2012	-1493828	703621	4999998	-1291014	189.10	1397	2922200
2039	0	2012	-1493828	703621	4999998	-1291020	189.10	1398	2922178
2040	0	2012	-1493827	703621	4999998	-1291028	189.10	1399	2922164
2041	0	2012	-1493826	703621	4999998	-1291035	189.10	1399	2922149
2042	0	2012	-1493826	703621	4999998	-1291045	189.10	1400	2922142
2043	0	2012	-1493826	703621	4999998	-1291052	189.10	1401	2922135
2044	0	2012	-1493826	703621	4999998	-1291060	189.10	1402	2922128
2045	0	2012	-1493826	703621	4999998	-1291067	189.10	1402	2922128
2046	0	2012	-1493826	703621	4999998	-1291075	189.10	1403	2922128
2047	0	2012	-1493826	703620	4999998	-1291079	189.10	1403	2922113

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*From March 1997

Western 5B void water balances – Option 2 (continued)

Year	*GW inflow* *m^3*	*Runoff* *m^3*	*Evap.* *m^3*	*Rainfall* *m^3*	*Stream flow* *m^3*	*Leakage* *m^3*	*Water level* *m AHD*	*TDS* *mg/L*	*Overflow* *m^3*
2048	0	2012	-1493826	703620	4999998	-1291087	189.10	1404	2922113
2049	0	2012	-1493826	703620	4999998	-1291094	189.10	1405	2922113
2050	0	2012	-1493826	703620	4999998	-1291100	189.10	1405	2922113
2051	0	2012	-1493826	703620	4999998	-1291105	189.10	1406	2922113
2052	0	2012	-1493826	703620	4999998	-1291111	189.10	1406	2922113
2053	0	2012	-1493826	703620	4999998	-1291117	189.10	1407	2922113
2054	0	2012	-1493826	703620	4999998	-1291120	189.10	1407	2922099
2055	0	2012	-1493826	703620	4999998	-1291125	189.10	1407	2922099
2056	0	2012	-1493826	703620	4999998	-1291131	189.10	1408	2922099
2057	0	2012	-1493826	703620	4999998	-1291135	189.10	1408	2922099
2058	0	2012	-1493826	703620	4999998	-1291139	189.10	1409	2922099
2059	0	2012	-1493826	703620	4999998	-1291143	189.10	1409	2922084
2060	0	2012	-1493825	703620	4999998	-1291146	189.10	1409	2922084
2061	0	2012	-1493825	703620	4999998	-1291148	189.10	1410	2922070
2062	0	2012	-1493825	703620	4999998	-1291152	189.10	1410	2922070
2063	0	2012	-1493825	703620	4999998	-1291155	189.10	1410	2922070
2064	0	2012	-1493825	703620	4999998	-1291159	189.10	1411	2922070
2065	0	2012	-1493825	703620	4999998	-1291162	189.10	1411	2922070
2066	0	2012	-1493825	703620	4999998	-1291166	189.10	1411	2922070
2067	0	2012	-1493825	703620	4999998	-1291170	189.10	1412	2922070
2068	0	2012	-1493825	703620	4999998	-1291172	189.10	1412	2922070
2069	0	2012	-1493825	703620	4999998	-1291175	189.10	1412	2922070
2070	0	2012	-1493825	703620	4999998	-1291177	189.10	1412	2922070
2071	0	2012	-1493825	703620	4999998	-1291180	189.10	1412	2922070
2072	0	2012	-1493825	703620	4999998	-1291183	189.10	1413	2922070
2073	0	2012	-1493825	703620	4999998	-1291185	189.10	1413	2922070
2074	0	2012	-1493825	703620	4999998	-1291188	189.10	1413	2922070
2075	0	2012	-1493825	703620	4999998	-1291190	189.10	1413	2922070
2076	0	2012	-1493825	703620	4999998	-1291193	189.10	1414	2922070
2077	0	2012	-1493825	703620	4999998	-1291195	189.10	1414	2922070
2078	0	2012	-1493825	703620	4999998	-1291197	189.10	1414	2922070
2079	0	2012	-1493825	703620	4999998	-1291199	189.10	1414	2922070
2080	0	2012	-1493825	703620	4999998	-1291201	189.10	1414	2922070
2081	0	2012	-1493825	703620	4999998	-1291204	189.10	1414	2922070
2082	0	2012	-1493825	703620	4999998	-1291208	189.10	1415	2922084
2083	0	2012	-1493825	703620	4999998	-1291208	189.10	1415	2922070
2084	0	2012	-1493825	703620	4999998	-1291210	189.10	1415	2922070
2085	0	2012	-1493825	703620	4999998	-1291212	189.10	1415	2922070
2086	0	2012	-1493825	703620	4999998	-1291213	189.10	1415	2922070
2087	0	2012	-1493825	703620	4999998	-1291215	189.10	1415	2922070
2088	0	2012	-1493825	703620	4999998	-1291216	189.10	1416	2922070
2089	0	2012	-1493825	703620	4999998	-1291218	189.10	1416	2922070
2090	0	2012	-1493825	703620	4999998	-1291219	189.10	1416	2922070
2091	0	2012	-1493825	703620	4999998	-1291220	189.10	1416	2922070
2092	0	2012	-1493824	703620	4999998	-1291220	189.10	1416	2922056
2093	0	2012	-1493824	703620	4999998	-1291221	189.10	1416	2922056
2094	0	2012	-1493824	703620	4999998	-1291223	189.10	1416	2922056
2095	0	2012	-1493824	703620	4999998	-1291224	189.10	1417	2922056
2096	0	2012	-1493824	703620	4999998	-1291225	189.10	1417	2922056

Western 5B void water balances – Option 3

(streamflow diversion: 5 x 10^6 m^3/year until 2002 then 2 x 10^6 m^3/year for 94 years)

Year	*GW inflow* *m^3*	*Runoff* *m^3*	*Evap.* *m^3*	*Rainfall* *m^3*	*Stream flow* *m^3*	*Leakage* *m^3*	*Water level* *m AHD*	*TDS* *mg/L*	*Overflow* *m^3*
1997*	695935	240295	-54875	37051	0	0	128.88	613	0
1998	1762265	219523	-198472	115193	0	0	141.87	679	0
1999	2305812	170276	-467784	246520	4999998	0	163.98	959	0
2000	1864041	103253	-850871	425247	4999998	0	175.53	1027	0
2001	745555	57329	-1130429	547710	4999998	-2277	182.68	1082	0
2002	74492	25169	-1333159	633472	4999998	-419907	187.40	1132	0
2003	0	9097	-1434605	676330	1999998	-920163	187.77	1169	0
2004	0	7263	-1446749	681347	1999998	-992464	188.05	1205	0
2005	0	6066	-1455892	685120	1999998	-1047130	188.25	1239	0
2006	0	5234	-1462782	687962	1999998	-1088482	188.41	1271	0
2007	0	4638	-1467975	690102	1999998	-1119779	188.53	1302	0
2008	0	4203	-1471890	691714	1999998	-1143471	188.62	1331	0
2009	0	3883	-1474837	692927	1999998	-1161394	188.68	1359	0
2010	0	3647	-1477059	693842	1999998	-1174980	188.73	1386	0
2011	0	3471	-1478732	694530	1999998	-1185285	188.77	1412	0
2012	0	3341	-1479987	695047	1999998	-1193087	188.80	1437	0
2013	0	3244	-1480924	695432	1999998	-1198969	188.82	1460	0
2014	0	3173	-1481623	695720	1999998	-1203420	188.83	1483	0
2015	0	3120	-1482144	695933	1999998	-1206785	188.85	1504	0
2016	0	3081	-1482527	696090	1999998	-1209322	188.85	1525	0
2017	0	3052	-1482810	696207	1999998	-1211259	188.86	1545	0
2018	0	3032	-1483018	696292	1999998	-1212727	188.87	1563	0
2019	0	3017	-1483168	696353	1999998	-1213837	188.87	1581	0
2020	0	3006	-1483269	696395	1999998	-1214659	188.87	1599	0
2021	0	2999	-1483340	696423	1999998	-1215272	188.87	1615	0
2022	0	2994	-1483388	696442	1999998	-1215746	188.87	1631	0
2023	0	2991	-1483416	696455	1999998	-1216104	188.87	1646	0
2024	0	2990	-1483431	696461	1999998	-1216376	188.87	1660	0
2025	0	2989	-1483439	696463	1999998	-1216574	188.87	1674	0
2026	0	2990	-1483434	696460	1999998	-1216702	188.87	1687	0
2027	0	2991	-1483421	696455	1999998	-1216784	188.87	1700	0
2028	0	2992	-1483411	696449	1999998	-1216846	188.87	1712	0
2029	0	2994	-1483394	696443	1999998	-1216902	188.87	1723	0
2030	0	2995	-1483381	696438	1999998	-1216949	188.87	1734	0
2031	0	2997	-1483365	696431	1999998	-1216983	188.87	1745	0
2032	0	2998	-1483348	696424	1999998	-1217007	188.87	1755	0
2033	0	3000	-1483331	696416	1999998	-1217010	188.87	1764	0
2034	0	3002	-1483312	696409	1999998	-1217012	188.87	1773	0
2035	0	3004	-1483295	696402	1999998	-1217015	188.87	1782	0
2036	0	3005	-1483278	696394	1999998	-1217013	188.87	1790	0
2037	0	3007	-1483262	696387	1999998	-1217010	188.87	1798	0
2038	0	3009	-1483244	696380	1999998	-1217006	188.87	1806	0
2039	0	3010	-1483231	696375	1999998	-1217007	188.87	1813	0
2040	0	3011	-1483217	696369	1999998	-1217009	188.87	1820	0
2041	0	3013	-1483204	696363	1999998	-1217013	188.87	1827	0
2042	0	3014	-1483191	696358	1999998	-1217015	188.87	1833	0
2043	0	3015	-1483180	696353	1999998	-1217014	188.87	1840	0
2044	0	3016	-1483168	696348	1999998	-1217011	188.87	1845	0
2045	0	3018	-1483156	696343	1999998	-1217009	188.87	1851	0
2046	0	3019	-1483144	696338	1999998	-1217007	188.87	1856	0
2047	0	3020	-1483133	696333	1999998	-1217002	188.87	1861	0

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* From March 1997

Western 5B void water balances – Option 3 (continued)

Year	GW inflow m^3	Runoff m^3	Evap. m^3	Rainfall m^3	Stream flow m^3	Leakage m^3	Water level m AHD	TDS mg/L	Overflow m^3
2048	0	3021	-1483123	696329	1999998	-1216993	188.87	1866	0
2049	0	3022	-1483112	696325	1999998	-1216986	188.87	1871	0
2050	0	3023	-1483101	696320	1999998	-1216980	188.86	1875	0
2051	0	3024	-1483091	696316	1999998	-1216973	188.86	1880	0
2052	0	3025	-1483082	696313	1999998	-1216967	188.86	1884	0
2053	0	3026	-1483075	696308	1999998	-1216961	188.86	1887	0
2054	0	3026	-1483067	696305	1999998	-1216956	188.86	1891	0
2055	0	3027	-1483058	696301	1999998	-1216949	188.86	1895	0
2056	0	3028	-1483049	696299	1999998	-1216944	188.86	1898	0
2057	0	3029	-1483041	696296	1999998	-1216939	188.86	1901	0
2058	0	3030	-1483035	696293	1999998	-1216933	188.86	1904	0
2059	0	3030	-1483029	696290	1999998	-1216929	188.86	1907	0
2060	0	3031	-1483023	696287	1999998	-1216923	188.86	1910	0
2061	0	3031	-1483017	696284	1999998	-1216919	188.86	1913	0
2062	0	3032	-1483011	696282	1999998	-1216916	188.86	1916	0
2063	0	3033	-1483006	696279	1999998	-1216912	188.86	1918	0
2064	0	3033	-1482998	696277	1999998	-1216910	188.86	1920	0
2065	0	3034	-1482993	696275	1999998	-1216907	188.86	1923	0
2066	0	3034	-1482988	696273	1999998	-1216905	188.86	1925	0
2067	0	3035	-1482984	696271	1999998	-1216904	188.86	1927	0
2068	0	3035	-1482981	696270	1999998	-1216903	188.86	1929	0
2069	0	3035	-1482977	696268	1999998	-1216902	188.86	1931	0
2070	0	3036	-1482974	696266	1999998	-1216901	188.86	1932	0
2071	0	3036	-1482971	696265	1999998	-1216901	188.86	1934	0
2072	0	3036	-1482968	696264	1999998	-1216900	188.86	1936	0
2073	0	3037	-1482964	696262	1999998	-1216898	188.86	1937	0
2074	0	3037	-1482961	696261	1999998	-1216897	188.86	1939	0
2075	0	3037	-1482959	696260	1999998	-1216897	188.86	1940	0
2076	0	3038	-1482956	696259	1999998	-1216896	188.86	1942	0
2077	0	3038	-1482950	696257	1999998	-1216894	188.86	1943	0
2078	0	3038	-1482946	696256	1999998	-1216888	188.86	1944	0
2079	0	3039	-1482944	696254	1999998	-1216886	188.86	1945	0
2080	0	3039	-1482941	696253	1999998	-1216882	188.86	1947	0
2081	0	3039	-1482938	696252	1999998	-1216880	188.86	1948	0
2082	0	3039	-1482936	696251	1999998	-1216879	188.86	1949	0
2083	0	3040	-1482934	696250	1999998	-1216877	188.86	1950	0
2084	0	3040	-1482931	696249	1999998	-1216874	188.86	1951	0
2085	0	3040	-1482929	696248	1999998	-1216871	188.86	1952	0
2086	0	3040	-1482928	696247	1999998	-1216869	188.86	1953	0
2087	0	3040	-1482926	696247	1999998	-1216869	188.86	1953	0
2088	0	3041	-1482924	696246	1999998	-1216869	188.86	1954	0
2089	0	3041	-1482923	696245	1999998	-1216868	188.86	1955	0
2090	0	3041	-1482923	696245	1999998	-1216870	188.86	1956	0
2091	0	3041	-1482921	696244	1999998	-1216872	188.86	1956	0
2092	0	3041	-1482920	696244	1999998	-1216873	188.86	1957	0
2093	0	3041	-1482919	696243	1999998	-1216873	188.86	1958	0
2094	0	3041	-1482918	696243	1999998	-1216873	188.86	1958	0
2095	0	3041	-1482917	696242	1999998	-1216870	188.86	1959	0
2096	0	3042	-1482916	696242	1999998	-1216870	188.86	1959	0

Western 5B void water balances – Option 4

(streamflow diversion: 5 x 10^6 m^3/year until 2002 then 0 m^3/year for 94 years)

Year	*GW inflow* *m^3*	*Runoff* *m^3*	*Evap.* *m^3*	*Rainfall* *m^3*	*Stream flow* *m^3*	*Leakage* *m^3*	*Water level* *m AHD*	*TDS* *mg/L*	*Overflow* *m^3*
1997*	695935	240295	-54875	37051	0	0	128.88	613	0
1998	1762265	219523	-198472	115193	0	0	141.87	679	0
1999	2305812	170276	-467784	246520	4999998	0	163.98	959	0
2000	1864041	103253	-850871	425247	4999998	0	175.53	1027	0
2001	745555	57329	-1130429	547710	4999998	-2277	182.68	1082	0
2002	74492	25169	-1333159	633472	4999998	-419907	187.40	1132	0
2003	0	13776	-1403388	663851	0	-726683	185.74	1166	0
2004	0	22193	-1349402	641407	0	-412205	184.44	1200	0
2005	0	28655	-1308150	624176	0	-174832	183.43	1236	0
2006	15131	33599	-1276697	610992	0	-10348	182.65	1272	0
2007	142225	37363	-1252810	600954	0	0	182.05	1305	0
2008	244466	40222	-1234711	593328	0	0	181.60	1337	0
2009	320840	42398	-1220967	587526	0	0	181.25	1366	0
2010	378173	44056	-1210511	583107	0	0	180.98	1394	0
2011	421396	45320	-1202544	579734	0	0	180.78	1421	0
2012	454081	46286	-1196466	577159	0	0	180.62	1447	0
2013	478853	47024	-1191824	575191	0	0	180.50	1472	0
2014	497662	47588	-1188274	573686	0	0	180.41	1496	0
2015	511957	48020	-1185559	572533	0	0	180.34	1520	0
2016	522827	48351	-1183480	571651	0	0	180.28	1543	0
2017	531131	48607	-1181880	570971	0	0	180.24	1566	0
2018	537455	48802	-1180650	570448	0	0	180.21	1588	0
2019	542273	48953	-1179702	570046	0	0	180.18	1611	0
2020	545938	49070	-1178972	569736	0	0	180.17	1633	0
2021	548749	49161	-1178403	569493	0	0	180.15	1655	0
2022	550874	49231	-1177963	569306	0	0	180.14	1677	0
2023	552507	49286	-1177617	569158	0	0	180.13	1699	0
2024	553743	49329	-1177344	569043	0	0	180.12	1721	0
2025	554674	49364	-1177130	568952	0	0	180.12	1743	0
2026	555391	49392	-1176957	568877	0	0	180.11	1765	0
2027	555935	49414	-1176816	568817	0	0	180.11	1786	0
2028	556329	49432	-1176702	568769	0	0	180.11	1808	0
2029	556621	49447	-1176610	568729	0	0	180.10	1830	0
2030	556844	49460	-1176529	568695	0	0	180.10	1851	0
2031	557008	49471	-1176460	568665	0	0	180.10	1873	0
2032	557139	49481	-1176398	568638	0	0	180.10	1895	0
2033	557243	49491	-1176341	568613	0	0	180.09	1917	0
2034	557311	49499	-1176289	568591	0	0	180.09	1938	0
2035	557330	49505	-1176246	568574	0	0	180.09	1960	0
2036	557329	49511	-1176209	568558	0	0	180.09	1982	0
2037	557323	49518	-1176171	568542	0	0	180.09	2003	0
2038	557314	49523	-1176135	568526	0	0	180.09	2025	0
2039	557304	49529	-1176099	568510	0	0	180.09	2046	0
2040	557290	49535	-1176064	568495	0	0	180.09	2068	0
2041	557273	49541	-1176029	568479	0	0	180.09	2090	0
2042	557255	49546	-1175995	568464	0	0	180.08	2111	0
2043	557239	49552	-1175960	568449	0	0	180.08	2133	0
2044	557222	49558	-1175925	568434	0	0	180.08	2155	0
2045	557204	49563	-1175890	568419	0	0	180.08	2176	0
2046	557183	49569	-1175856	568405	0	0	180.08	2198	0
2047	557161	49574	-1175822	568390	0	0	180.08	2220	0

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* From March 1997

Western 5B void water balances – Option 4 (continued)

Year	*GW inflow* *m^3*	*Runoff* *m^3*	*Evap.* *m^3*	*Rainfall* *m^3*	*Stream flow* *m^3*	*Leakage* *m^3*	*Water level* *m AHD*	*TDS* *mg/L*	*Overflow* *m^3*
2048	557138	49580	-1175788	568375	0	0	180.08	2241	0
2049	557113	49585	-1175755	568361	0	0	180.08	2263	0
2050	557088	49591	-1175722	568346	0	0	180.08	2285	0
2051	557063	49596	-1175689	568332	0	0	180.08	2306	0
2052	557038	49601	-1175655	568318	0	0	180.07	2328	0
2053	557013	49607	-1175622	568303	0	0	180.07	2350	0
2054	556991	49612	-1175589	568288	0	0	180.07	2371	0
2055	556968	49618	-1175555	568274	0	0	180.07	2393	0
2056	556943	49623	-1175522	568259	0	0	180.07	2415	0
2057	556918	49629	-1175489	568245	0	0	180.07	2436	0
2058	556893	49634	-1175456	568231	0	0	180.07	2458	0
2059	556871	49640	-1175422	568216	0	0	180.07	2480	0
2060	556849	49645	-1175388	568201	0	0	180.07	2501	0
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2069	556626	49694	-1175088	568071	0	0	180.06	2696	0
2070	556605	49699	-1175055	568056	0	0	180.06	2718	0
2071	556585	49705	-1175021	568041	0	0	180.06	2740	0
2072	556563	49710	-1174987	568027	0	0	180.05	2761	0
2073	556542	49716	-1174953	568012	0	0	180.05	2783	0
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2081	556376	49760	-1174681	567894	0	0	180.04	2956	0
2082	556355	49766	-1174648	567879	0	0	180.04	2978	0
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2091	556169	49816	-1174341	567746	0	0	180.03	3173	0
2092	556150	49821	-1174307	567731	0	0	180.03	3195	0
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2094	556109	49832	-1174239	567702	0	0	180.03	3238	0
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2096	556068	49843	-1174171	567672	0	0	180.03	3281	0

WATER AND RIVERS COMMISSION
Hyatt Centre
3 Plain Street
East Perth
Western Australia 6004
Telephone (08) 9278 0300
Facsimile (08) 9278 0301
Website http://www.wrc.wa.gov.au