



Department of Water  
Government of Western Australia



# Groundwater Model of the Collie Basin Western Australia

Hydrogeological Record Series

REPORT NO. HG 15  
JANUARY 2007





Department of **Water**  
Government of **Western Australia**

# Groundwater Model of the Collie Basin Western Australia

by

Q Zhang, S Varma, J Bradley, J Schaeffer

Water Resource Management Division

Department of Water

Department of Water  
Hydrogeological Record Series  
Report No. HG 15  
January 2007

## Acknowledgments

The modelling project received important scientific support from the Collie Basin Modelling Steering Group that consisted of representatives from CSIRO (Dr Anthony Smith), the Griffin Coal, Wesfarmers Coal and Western Power (Mr Ian Brunner, URS) and Water and Rivers Commission (Phillip Kalaitzis, Sunil Varma, Alex Kern and Chris O'Boy). The Collie Basin groundwater modelling project team is grateful to the members of the Collie Basin Research Steering Committee for project initiation and regular support. Sunil Varma of Department of Water, and Qi Zhang, Jurgen Schaeffer and John Bradley of GHD have contributed to this report.

For more information contact:

Water Resource Management Division  
Department of Water  
Level 4, The Atrium  
168 St Georges Terrace  
PERTH WA 6000

Telephone: 08 6364 7600

Facsimile: 08 6364 7601

## Recommended reference

The recommended reference for this publication is: Zhang, Q., Varma, S., Bradley, J., Schaeffer, J., 2007, *Groundwater Model of the Collie Basin, Western Australia*, Department of Water, Government of Western Australia, Hydrogeological Record Series Report No. HG15.

### **We welcome your feedback**

A publication feedback form can be found at the back of this publication, or online at [www.water.wa.gov.au](http://www.water.wa.gov.au)

ISSN 1329-542X

January 2007

Cover photograph:

*Diversion of saline water from Collie River East into an open cut mine void, August 2005*  
G.L. Kernick, PageSetter Design

# Contents

Summary .....	viii
1 Introduction .....	1
1.1 Project background.....	1
1.2 Data collection .....	4
1.2.1 Stratigraphy .....	4
1.2.2 Groundwater levels.....	5
1.2.3 Groundwater abstraction .....	5
1.2.4 Rainfall data.....	5
1.2.5 Streamflow data.....	6
1.2.6 Evaporation data.....	6
1.2.7 Pool data.....	6
2 Geological and hydrogeological overview .....	7
2.1 Basin structure.....	7
2.1.1 Faulting.....	7
2.1.2 Folding.....	9
2.2 Stratigraphy .....	9
2.3 Hydrostratigraphy .....	9
2.3.1 Precambrian basement.....	9
2.3.2 Stockton Group.....	9
2.3.3 Collie Group.....	10
2.3.4 Nakina Formation and surficial sediments.....	13
2.4 Groundwater age and confinement .....	14
2.5 Hydraulic properties of aquifers .....	14
2.6 Important aspects of mining.....	15
2.6.1 General.....	15
2.6.2 Underground mines .....	15
2.6.3 Open cut mines.....	16
3 Development of the numerical model.....	17
3.1 General.....	17

3.2	Selection of a suitable modelling package.....	17
3.3	Model domain .....	18
3.4	Boundary conditions .....	20
3.5	Model layers .....	20
3.5.1	General.....	20
3.5.2	Representation of model layers.....	23
3.5.3	Simulation of vertical leakage between hydrostratigraphic units.....	26
3.6	Model grid.....	26
3.7	Layer type and property.....	29
3.8	Rainfall recharge and discharge.....	29
3.8.1	General.....	29
3.8.2	Representation of recharge and discharge in the model.....	29
3.8.3	Recharge zones.....	30
3.8.4	Discharge zones.....	30
3.8.5	Adjustment of recharge during calibration .....	32
3.9	Representation of faults.....	33
3.10	Representation of mines.....	35
3.10.1	Open cut mines.....	35
3.10.2	Underground mines .....	35
3.11	Surface water features.....	36
3.11.1	Rivers.....	36
3.11.2	Creeks and wetlands .....	37
3.12	Wells .....	38
3.12.1	Issues with bore construction .....	38
3.12.2	Wellfields .....	38
3.12.3	Groundwater abstraction prior to 1984 .....	39
3.13	Model test runs .....	40
4	Model Calibration .....	41
4.1	Calibration strategy.....	41
4.2	Steady state calibration .....	41
4.2.1	Pre-stress steady state watertable .....	41
4.2.2	Calibration measures.....	43
4.2.3	Summary .....	47

4.3	Transient calibration.....	48
4.3.1	General.....	48
4.3.2	Calibration period and initial conditions.....	51
4.3.3	Discretisation of time.....	51
4.3.4	Synchronisation of models.....	51
4.3.5	Calibration measures.....	51
4.4	Sensitivity analysis.....	60
5	Prediction simulations.....	63
5.1	Simulating water level recovery in Cardiff Sub-basin.....	64
5.1.1	Groundwater recovery in the Cardiff Sub-basin.....	64
5.2	Simulating Western 5B mine void water levels.....	65
5.3	Groundwater discharge to the Collie River.....	67
6	Model assumptions and limitations.....	68
6.1	Data gaps and assumptions.....	68
6.2	Model limitations.....	69
7	Conclusions.....	71
8	Bibliography.....	75
	Appendix A: Modelling Surface Water and Groundwater Interaction – Q Zhang.....	78
	Appendix B: Water balance of the Collie Basin.....	87
	Appendix C: Contours of surfaces and isopachs of the Collie Basin strata.....	88
	Appendix D: Potentiometric heads in model layers.....	107
	Glossary.....	117
	Other publications in the HG Series.....	120
	Publication feedback form.....	121

# Figures

1. Location.....	x
2. Subcrop geology .....	8
3. Stratigraphic sections.....	11
4. Revised geological section.....	12
5. Model boundary and surface features.....	19
6. Model cross-section .....	24
7. Model fence diagram.....	25
8. Use of dummy layers (Aquaterra, 1999) .....	27
9. Model grid .....	28
10. Model recharge zones.....	31
11. Location of faults .....	34
12. Coal production and mine dewatering (Cardiff Sub-basin) .....	39
13. Interpreted historical dewatering .....	40
14. Area of the Collie Basin affected by abstraction .....	42
15. Sample hydrographs .....	44
16. Conceptual pre-mining watertable .....	45
17. Observed vs simulated heads in steady state calibration .....	47
18. Flow patterns in vertical cross section – steady state flow.....	48
19. Flow patterns in section (SW-NE) .....	49
20. Flow patterns in section (NW-SE) .....	50
21. Calibration hydrographs (Set 1) .....	54
22. Calibration hydrographs (Set 2) .....	55
23. Calibration hydrographs (Set 3) .....	56
24. Calibration hydrographs (Set 4) .....	57

25. Calibration hydrographs (Set 5) .....	58
26. Calibration hydrographs (Set 6) .....	59
27. Watertable drawdown .....	61
28. Volumetric recovery in Cardiff Sub-basin.....	65
29. Iterative computation of WO5B void water level .....	66
30. Water level recovery in WO5B void .....	67

## Tables

1. Summary of tasks and deliverables .....	3
2. Generalised stratigraphy of the Collie Basin.....	10
3. Summary of hydraulic parameters determined by pumping tests .....	15
4. Correlation of model layers .....	21
5. Rainfall recharge applied to the model.....	32
6. Riverbed conductance .....	36
7. Volumetric budget for entire model domain – steady state model .....	46
8. Collie Basin model – hydraulic parameters.....	53
9. Water balance components from the transient model.....	59
10. List of scenarios for prediction simulations .....	63
11. Groundwater discharge to rivers .....	67

## Summary

The Collie Basin Research Steering Committee, formed in 1997 upon recommendation of the Collie Water Advisory Group (CWAG), identified that sustainable yields of the Permian sediments of Collie Basin, knowledge of groundwater levels recovery and options for enhancing recovery in the Collie Basin with respect to management of pools, and rehabilitation of abandoned open cut mine voids are the key water resources management issues in the basin.

Upon the recommendation of the Collie Basin Research Steering Committee, the Water and Rivers Commission developed a three-dimensional groundwater flow model under a three-stage modelling program. Prior to construction of the numerical model, a comprehensive review of literature was undertaken to enable an understanding of the hydrogeologically and hydrologically significant features of the Collie Basin. Data were interpreted to produce surfaces, isopachs, and cross-sections of the nine units that represent the sedimentary sequence of the basin.

In particular the model has enabled the following:

- Improved understanding of the groundwater flow patterns of the Collie Basin, and sustainable yields of the individual sedimentary units;
- Estimation of groundwater recovery in the basin particularly near the pools of the Collie River South Branch;
- Assessment of options for enhancing recovery of groundwater levels including artificial recharge;
- Establishment of the water balance of the open cut mine voids;
- Assessment of impact of several scenarios of groundwater abstraction and climate change on the groundwater resources of the Collie Basin.

Data collected during this project include stream levels and flows, rainfall and evaporation data, groundwater levels, bore construction, abstraction and screened intervals. These have been incorporated into a number of standardised data sets for input to the model.

The model of the Collie Basin has been developed using MODFLOW and the GMS graphical user interface. The model has been calibrated under steady state and transient conditions with available data. In areas where no observation bores are available, the simulated watertable configuration matches qualitatively with the conceptual watertable. In addition, flow directions across the basin also match those indicated in the literature.

The Collie River has been simulated in the model using the River Package in MODFLOW. A reasonable response between river-groundwater interaction and groundwater abstraction has been obtained and a methodology for modelling surface water-groundwater interaction has been established.

Several predictive simulations have been carried out using the model to test the ability of the model to predict the impact of abstraction on groundwater levels in

the basin, and groundwater discharge to the Collie River. The results of the predictive simulations are in agreement with results of previous work in the basin.

Analysis of volumetric recovery for the Cardiff Sub-basin shows that about 90% recovery will be achieved in 50 years in the absence of any pumping in the Cardiff-Sub-basin. This recovery would be slower if a reduction of rainfall took place across the basin. Modelling showed that only 20% recovery would be achieved in this time-frame if pumping continued in the Cardiff Sub-basin at current levels.

Simulation of water levels in Western 5B void (Lake Kepwari) shows that without streamflow diversion, the water level in the void will recover by only 17 m before reaching steady state; however, with streamflow diversion of 5 GL/yr the water level in the void will recover by 40 m and overflow in 5 years.

Modelling predicts that the groundwater discharge to the Collie River will recover from about 6 GL/yr presently to around 12 GL/yr in 50 years time if there was no further pumping in the Cardiff Sub-basin.

The development and accuracy of the Collie Basin groundwater model has been influenced by a number of important data gaps. In addition to the assumptions made, a number of limitations exist, both in the data available to produce a model and in the model itself. The model may be improved with ongoing work, as the conceptual understanding of the Collie Basin hydrogeology improves. Interpretation of model outputs for above mentioned applications should therefore take into account the complex nature of the Collie Basin structure, the data assumptions and limitations of the model.

The model development has facilitated the consolidation of existing conceptual knowledge on the Collie Basin hydrogeology. The Collie Basin groundwater flow model will form a valuable platform from which regional management strategies and plans can be formulated.

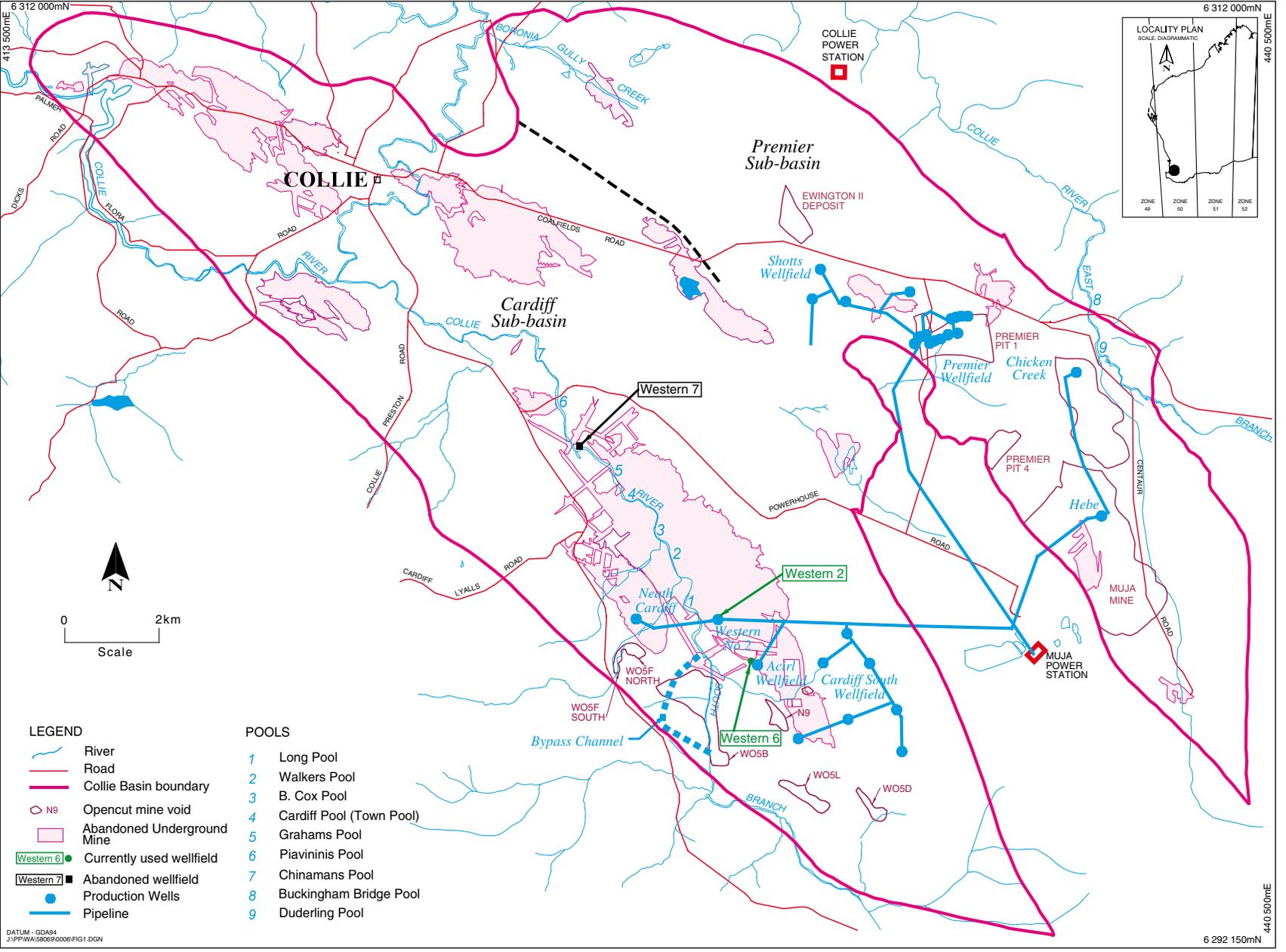


Figure 1. Location

- LEGEND**
- River
  - Road
  - Collie Basin boundary
  - N9 Opencut mine void
  - Abandoned Underground Mine
  - Western 6 Currently used wellfield
  - Western 7 Abandoned wellfield
  - Production Wells
  - Pipeline
- POOLS**
- 1 Long Pool
  - 2 Walkers Pool
  - 3 B. Cox Pool
  - 4 Cardiff Pool (Town Pool)
  - 5 Grahams Pool
  - 6 Piavininis Pool
  - 7 Chinamans Pool
  - 8 Buckingham Bridge Pool
  - 9 Duderling Pool

DATUM - GDA84  
 J:\PP\WA\58069\0006\FIG1.DGN

6 292 150mE  
 440 500mE

# 1 Introduction

## 1.1 Project background

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. The 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 (Fig. 1). It is surrounded by Archaean granitic rocks of the Yilgarn Craton. The surface area of the basin is about 225 km<sup>2</sup>. It is bilobate in shape and is filled with Permian and Cretaceous sediments having a maximum thickness of about 1500 m.

Coal from the Collie Basin forms 48% of the identified fossil fuel energy in Western Australia; about 85% of this is used for electricity generation. The coal from the basin provides fuel for generation of about 70% of the electricity that is consumed in the southwest of Western Australia (Office of Energy, 2003). The basin contains substantial resources of fresh groundwater, within a complex hydrogeological setting, that are important for both coal mining and power generation. The control of groundwater discharge to the open cut mines is essential to ensure safe and efficient operation. Groundwater from the basin is used for cooling at the Muja and Collie Power Stations. A good understanding of the hydrogeology and groundwater resources of the basin is important for the sustainable use of the groundwater resource and protection of the associated environment.

In 1996, the Collie Water Advisory Group (CWAG) (Collie Water Advisory Group, 1996) recommended that the Department of Water (then Water and Rivers Commission) carry out detailed hydrogeological investigations 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 to supplement the existing network of bores. Accordingly, an investigation by the Water and Rivers Commission comprising large scale drilling and monitoring of bores was carried out during 1998-2001. This resulted in drilling of 80 monitoring bores. The results of the investigation have enhanced the understanding of the hydrogeology and groundwater resources of the basin, in particular the regional effects of groundwater abstraction, surface water and groundwater interaction, and water balance (Varma, 2002).

The Collie Basin Research Steering Committee, formed in 1997 upon recommendation of CWAG, identified that sustainable yields of the Permian sediments of Collie Basin, knowledge of groundwater levels recovery and options for enhancing recovery in the Collie Basin with respect to management of pools, and rehabilitation of abandoned open cut mine voids are the key water resources management issues in the basin. In 1999, the Collie Basin Research Steering Committee recommended that Water and Rivers Commission develop a groundwater flow model of the Collie Basin that would address these key issues by achieving the following:

- Improved understanding of the groundwater flow patterns in a multi-layer aquifer system of the Collie Basin, and sustainable yields of individual sedimentary units;
- Estimation of groundwater recovery within the Permian sediments, in particular near the pools of the Collie River South Branch;
- Study of groundwater-river interaction to aid river pool augmentation, and assessment of impact of reduced streamflow volumes;
- Assessment of options for enhancing recovery of groundwater levels including artificial recharge;
- Establishment of the water balance of the open cut mine voids in Cardiff Sub-basin and their impact on the quality of groundwater and river water including pools, based on a number of options of streamflow diversion volumes;
- Evaluation of the effectiveness of artificial supplementation of the pools in the Collie River South Branch and its impact on recovery of groundwater levels in the Cardiff Sub-basin.

Development of a numerical groundwater flow model of the Collie Basin is the second phase of a two-phase modelling program. The first phase comprised development of a conceptual model of the Cardiff Sub-Basin and in particular the river-groundwater interaction and impact of open cut mine voids, and was carried out by Aquaterra Consulting Pty Ltd. During this first phase, the hydrogeological features of the sub-basin were described, and a conceptual hydrogeological model was developed. In addition, a suitable modelling package and a staged approach for carrying out the proposed numerical modelling were recommended (Aquaterra, 1999). Aquaterra recommended that a regional scale model of the Collie Basin with local refinement is required to simulate the interactions between the recovering watertable and the river pools and mine voids. Consequently, Geo-Eng (now GHD) was engaged by the Water and Rivers Commission to undertake the second phase of the modelling program. The objective of the contract was:

*'...to develop a simple regional scale groundwater model of the basin with detailed surface water-groundwater interaction features that could provide quantified predictions of groundwater levels in the basin, and water levels in the river and mine voids, based on different scenarios of abstraction, river supplementation, artificial groundwater recharge and streamflow diversion into the mine voids'.*

The modelling was undertaken in three stages as detailed in Table 1. Stages I and II were completed by Geo-Eng. Further refinement of the model at the end of Stage II, and Stage III were carried out in-house by Water and Rivers Commission with in-house modelling support from Geo-Eng. This report summarises the Stage I outcomes and describes in detail the results of Stages II and III of the numerical modelling.

The entire modelling project underwent an ongoing independent review from the Collie Basin Modelling Steering Group that consisted of representatives from CSIRO and URS. The development of this model conforms very well with the Murray Darling Basin groundwater flow modelling guidelines (MDBC, 2001).

Table 1. Summary of tasks and deliverables

Stage	Particulars	Tasks	Deliverables
I	Data collection	Undertake literature review, data collation and processing to establish data sets for definition of aquifer geometry, subsequent model calibration, verification and prediction. Data would be sourced from coal mining companies, Western Power, Department of Minerals and Energy and Water and Rivers Commission. The cores of exploratory bores drilled in the basin, which are held at the core libraries of the mining companies and the Department of Minerals and Energy, should also be inspected and possibly analysed to obtain the hydraulic properties of the Collie Basin sediments. Data should include, but not be limited to, historical water levels, streamflow volumes, historical groundwater abstraction data, meteorological information, riverbed elevations, hydrostratigraphy and hydrochemistry.	Data sets in electronic spreadsheet, hydrogeological maps and a brief explanatory note. Indication of any additional data requirement. Initially a draft report should be submitted and after review and approval by the Project Manager, 15 hard copies and an electronic version of the report and data sets will be required.
II	Development of the numerical model	Develop a simple calibrated basin-scale numerical model of the entire Collie Basin with 'nested' local features to represent the Collie River South Branch, river pools and open cut mine voids in Cardiff Sub-basin. Undertake model verification and sensitivity analysis. The numerical model should incorporate structural features, boundaries, geometry and other salient features of Collie Basin. Establish a groundwater balance of Collie Basin and sustainable yields of the aquifer layers.	A calibrated 3D groundwater flow model of Collie Basin with 'nested' local features as described above. A comprehensive report including methodologies adopted and findings of Stage II study (15 copies).
III	Prediction simulations	Run prediction simulations for a range of water resource management options to be agreed by the Water and Rivers Commission representative, with respect to changes in groundwater abstraction, river pool augmentation, river diversion to open cut mine void, river diversion/aquifer injection to enhance aquifer recovery, and open cut mine voids water balances	Presentation of model results and reporting, which should clearly specify the limitations of the model, and include CD-ROM copies of the model calibration and prediction data sets (input and output), and a copy of the modelling package software licensed to Water and Rivers Commission. A final report is required following the completion of Stage III covering all aspects of the study in a format that is of publication standard.

## 1.2 Data collection

Stage I of the Collie Basin Groundwater Modelling project comprised an extensive literature review and data collection for subsequent conceptualisation and construction of the model. It received input from private and government organisations and individuals with current and historical involvement in agricultural, mining, geological and hydrogeological investigations throughout the Collie Basin.

The Stage I of the project concentrated on reviewing and collecting all available hydrogeological data relating to the Collie Basin, and the production of data sets and a conceptual model for use in the Stage II of the project. The Stage I of the project was fully undertaken by Geo-Eng. The work also included preparation of revised cross-sections of the basin, maps showing location of data and hydrogeological surfaces, tables summarising hydraulic parameters of the formations and schematic drawings of the geology and conceptual models utilised for this stage of the project. Specific data collated during this stage of the project include:

- geological surfaces
- groundwater extraction rates
- structural data
- surface topography
- revised geological cross-sections
- groundwater levels
- hydrological data including streamflow and rainfall
- conceptual hydrogeological models
- proposed modelling layers.

### 1.2.1 Stratigraphy

Records of stratigraphic details of the basin are sparse. However, the longitudinal sections of Le Blanc Smith (1993) contained useful stratigraphic information. As these sections represented 'hung' sections with the zero datum represented by one of the coal seams, the sections alone could not be used to provide reduced levels of the stratigraphic horizons. Therefore, the original data files from Le Blanc Smith (1993) were obtained from Geological Survey of Western Australia, that contained the reduced levels of the bore collars that were used to prepare the stratigraphic sections correctly.

Other data included a set of four cross-sections obtained from Wesfarmers Coal Ltd. These included three of the sections that were used to create the schematic section shown in Figure 3 in Le Blanc Smith (1993). The original cross-sections obtained from Wesfarmers Coal contained information not present on later schematic representations, whereas the schematic sections in Le Blanc Smith (1993) included new stratigraphic data not shown on the original sections. As a result, a new set of cross-sections and a block diagram based on these were generated for this project (Geo-Eng, 2000, *Figures 24-28*). These new sections include the stratigraphic intervals that represent the model layers described in this report.

Additional information was obtained from the reduced level of the Permian subcrop presented in Plate 2 of Le Blanc Smith (1993). The reduced level of the subcrop boundaries, based on the contours generated for the base of Nakina Formation (Plate 2 in Appendix C), was digitised, and the variable fault throws indicated on Plate 2 of Le Blanc Smith (1993) were used to indicate the magnitude of displacement of each model layer.

As a final step, this information was hand contoured taking into account any vertical displacement of layers as a result of faulting. The hand contours were digitised and further processed using Surfer, and are shown in Plates 2–9 provided in Appendix C of this report. Plate 1 shows the upper surface of the top layer, which is essentially the topographical elevation. The Surfer grid information for each layer was saved into an Excel spreadsheet, in a format for easy importing to the model.

### 1.2.2 Groundwater levels

Information on groundwater levels was obtained from a number of sources, but the main sources were the Water and Rivers Commission databases. Additional available data was sourced from mining companies and Western Power. The data sets have been put in a spreadsheet format and include bore location and construction data, and monthly water levels recorded since 1984.

### 1.2.3 Groundwater abstraction

Groundwater abstraction data from 1984 to 2006 has been obtained from paper records (Dames & Moore, 1997; Western Collieries Ltd, 1991), as well as some data files supplied by Western Power Corporation. Details on particular aquifer zones from which abstraction took place have been obtained from a number of sources. Some data sets have details of the aquifer that the bore is screened in – this has been interpreted to place the screened unit within a particular regional unit and hence the model layer. Several bores are listed as crossing layer boundaries, especially between the Nakina (or surficial) aquifer and the immediately underlying unit. These bores have been identified as being within multiple units.

### 1.2.4 Rainfall data

Records of daily rainfall have been obtained from the Commonwealth Bureau of Meteorology's database. Three main rainfall sites have been chosen to represent the Collie Basin:

- 009 628, Collie Post Office, 1907 to 2006;
- 009 666, McAlinden, 1945 to 2006;
- 009 738, Muja, 1962 to 2006.

These sites were selected due to their proximity to the Collie Basin and for their length of record.

### 1.2.5 Streamflow data

Streamflow data has been obtained from the Water and Rivers Commission HYDSYS database in daily and monthly format. Several sites within the Collie Basin were selected. However, only one gauged station exists on the South Branch, which is immediately downstream of the Chinamans Pool (Pool 7). Water quality sampling has been undertaken at all sites and results can be obtained if required. The sites selected, and the length of record, are:

- a. 612 001, Collie River East Branch, 1968 to 2006;
- b. 612 002, Collie River, Mungalup Tower, 1969 to 2006;
- c. 612 025, Camballan Creek, James Well, 1982 to 2006;
- d. 612 017, Harris River, Tallanalla Road, 1976 to 1992;
- e. 612 036, Harris River, Stubbs Farm, 1952 to 1977 (same site as 612 017);
- f. 612 034, Collie River South Branch, 1952 to 2006;
- g. 612 035, Collie River East Branch, Central Collie, intermittent data from 1952 to 1976 (river stage only after 1976 to 2006).

### 1.2.6 Evaporation data

Daily evaporation data has been collected for the Dwellingup Forestry (009 538) climate station for 1972 to present. Corrections have been previously made to the data to account for missing data and bird guards. Site adjustments have also been made from the original data to represent a specific location within the Collie region.

### 1.2.7 Pool data

Water level data for the seven significant pools of the South Branch and the Buckingham Bridge Pool of the East Branch (Pool 8) were obtained from Water and Rivers Commission records. Data for the pools includes longitudinal sections at each pool and cease to flow level. Water quality records including Electrical Conductivity (EC) readings at 25°C were also collected.

## 2 Geological and hydrogeological overview

### 2.1 Basin structure

The regional geology and hydrogeology of the Collie Basin has been described in detail by a number of authors. These include Lord (1952), Low (1958), Le Blanc Smith (1993), Moncrieff (1993), Mohsenzadeh (1998) and Varma (2002). The geology of the Collie Basin is most comprehensively described by Le Blanc Smith (1993), who updated the stratigraphic nomenclature to the current form. The basin contains mainly Permian-age sediments, up to 1500 metres thick (Western Collieries, 1991), that have been protected from erosion by down faulting into the Yilgarn Craton. The basin consists of two lobes, as was shown by a 1946 gravity survey (Chamberlain, 1947) and a later revision by Kevi (1990). The smaller and shallower of the lobes, on the eastern side of the basin, is known as the Premier Sub-basin, and the larger is the Cardiff Sub-basin on the western side. The Premier Sub-basin has been referred to in some reports, for example Australian Groundwater Consultants (1978), as the 'Shotts/Muja Sub-basin' which has been further subdivided into the Shotts Sub-basin in the northwest and the Muja Sub-basin in the southeast.

The sub-basins have a pronounced NW-SE orientation, in line with the major regional faults marking the basin boundaries (Figure 2). The regional down-thrust faulting that caused the formation of the basin has also caused pronounced faulting of the sediments, predominantly in the NW-SE orientation. There has been little lateral displacement along the fault planes, which are generally steeply dipping at angles of 60–90°.

#### 2.1.1 Faulting

It is believed that the folding and faulting have been caused by the same series of tectonic block movements that predate the deposition of the overlying Cretaceous Nakina Formation. The intra-basinal faults in the Permian sediments mostly have a northwesterly strike and commonly impinge at a low angle on the basin-bounding faults. The dominant kind of faulting in the basin is steep dip-slip with dip angles of 60–90°.

Faults are likely to be of substantial importance to groundwater movement within the basin, as:

- The faults will generally provide some restriction to the horizontal transmission of water. In part, this is due to a thin layer of fine-grained material that tends to occur on each fault plane. In addition to the barrier effect commonly observed on the fault plane itself, the faults tend to break the horizontal continuity of aquifers and this will also restrict flow along the aquifer planes.
- An important effect of the faults would be to increase vertical leakage between aquifers by breaking the horizontal continuity of aquitard layers. As these are generally thinner and are less prevalent than the sandstone aquifers, only a small amount of displacement is required to break the continuity of the aquitards.

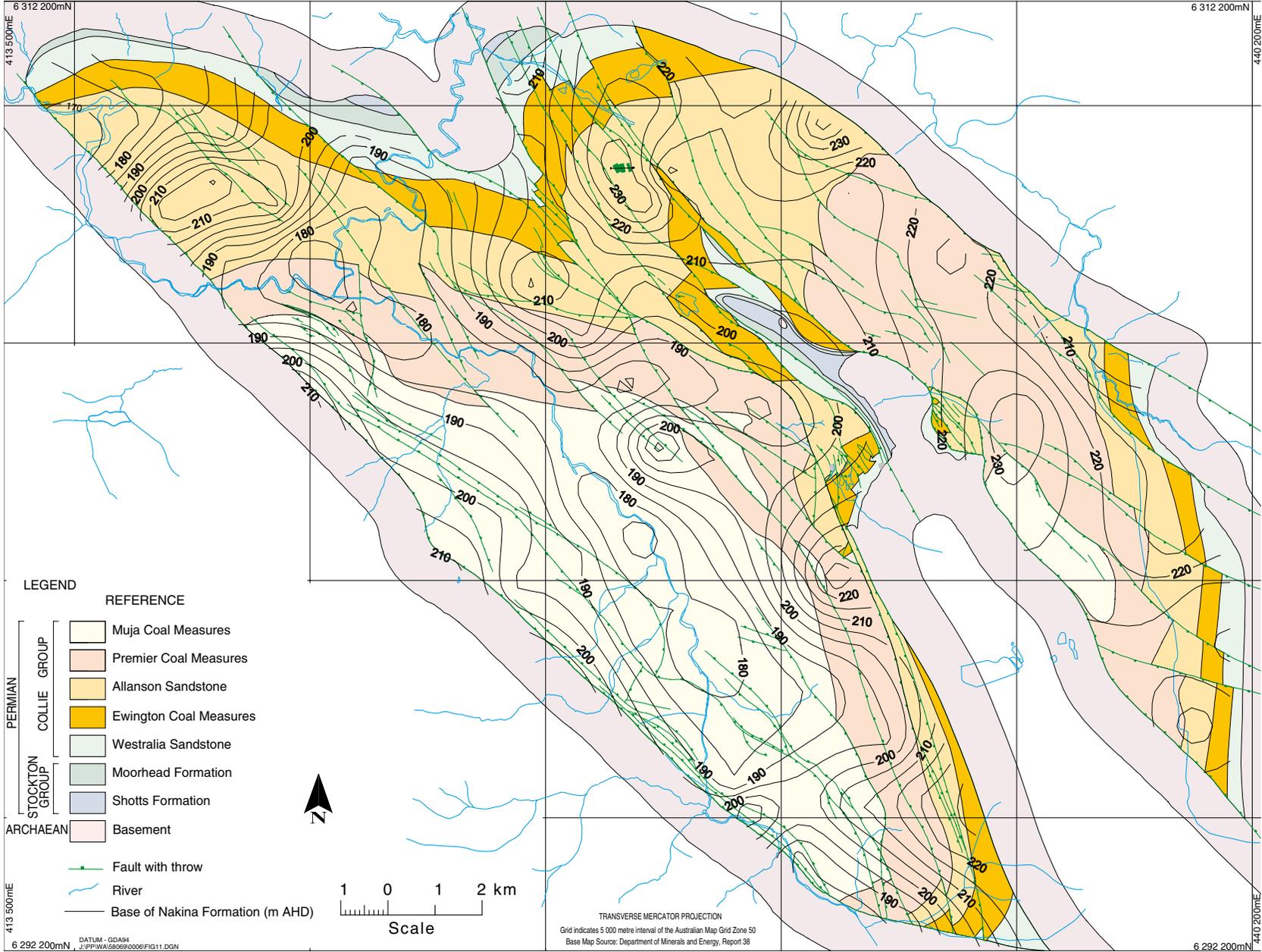


Figure 2. Subcrop geology

- Some faults may provide channels for drainage of groundwater into the deeper aquifers within the basin, depending on head differentials between aquifers. Coal mining adjacent to faults could also influence the hydraulic characteristics of the faults.
- The faults have a major role (along with folding) in causing the deep aquifers to subcrop on the base of the Nakina Formation near the southeastern and northern boundaries of each sub-basin, allowing enhanced downward leakage from surficial aquifers in these areas.

### 2.1.2 Folding

The regional folding and faulting has caused the deeper formations to subcrop on the base of the Nakina Formation at the southeastern and northern margins of each sub-basin. This further allows the transmission of drawdown from groundwater abstraction from lower stratigraphic units to the shallow strata that are relevant to maintenance of surface streams and pools.

## 2.2 Stratigraphy

The stratigraphy of the Collie Basin is summarised in Table 2. Geological sections from Le Blanc Smith (1993) are presented in Figure 3. An example of a revised cross-section prepared by Geo-Eng (2000) is presented in Figure 4.

## 2.3 Hydrostratigraphy

### 2.3.1 Precambrian basement

Australian Groundwater Consultants (AGC, 1978) believe that the major tectonic faulting that has formed the Collie Basin may have caused substantial fracturing of the basement rocks. These fractures in the basement could facilitate some flow of groundwater into the deep Permian aquifers under the influence of mine dewatering and abstraction. This may be more relevant in the Premier Sub-basin where the Moorhead Formation of low permeability, generally occurring between the basement and the Collie Group aquifers, may be thin or absent in places. The major basin boundary faults generally present a direct contact between the Permian aquifers and the surrounding craton. Archaean basement adjacent to the boundary faults, as observed in open cut mines and in drillhole cores, displays intense metamorphic foliation and fracturing (Le Blanc Smith, 1993).

### 2.3.2 Stockton Group

The groundwater potential of the Stockton Group is unknown. However, any useable groundwater resources are likely to be in the lowermost Shotts Formation, which is a diamictite, as the overlying Moorhead Formation is a laminated claystone. Some bores abstract groundwater from the Shotts Formation near the town of Collie where the unit occurs at a shallow depth.

Table 2. Generalised stratigraphy of the Collie Basin (after Le Blanc Smith, 1993)

Age	Group	Formation	Maximum thickness		Lithology
			Cardiff Sub-basin	Premier Sub-basin	
<b>Tertiary to Recent</b>	<b>Ungrouped</b>	Surficial sediments	4 m	4 m	Alluvium, colluvium, laterite
<b>Cretaceous</b>		Nakina Formation	20 m	15 m	Sandstone, mudstone
<b>Permian</b>	<b>Collie Group</b>	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
	<b>Stockton Group</b>	Moorhead Formation			Mudstone and tillite
		Shotts Formation	370 m	50 m	Gravel conglomerate and basement clasts, sandstone
<b>Archaean</b>				Granite, dolerite, metasediments	

### 2.3.3 Collie Group

#### 2.3.3.1 Aquifers

Le Blanc Smith (1993) indicates that the sand and sandstone units within the Collie Group are similar between the formations. The coal measures are differentiated from each other by the varying amounts of coal seams. The lithology of the Muja Coal Measures is differentiated from the underlying Premier Coal Measures principally by its having thicker sandstone beds and coal seams. Up to 60% of the Coal Measures sequence comprises sandstone. The remainder includes shale, siltstone and coal, and at least one third of the sequence comprises sandstones that are sufficiently coarse and free from shale interbeds to enable the economic extraction of groundwater sandstones (AGC, 1985). Allanson Sandstone and Westralia Sandstone are devoid of any coal seams.

A similar conclusion has been found in the current study by statistical examination of the lithologic logs produced by Le Blanc Smith (1993) for a bore in the Cardiff Sub-basin, which penetrates many of the Collie Group strata. A similar pattern of sedimentary cycles is seen throughout the Permian sequence. The entire Permian sequence consists of a series of numerous sand/sandstone aquifers typically 6–9 m thick that are

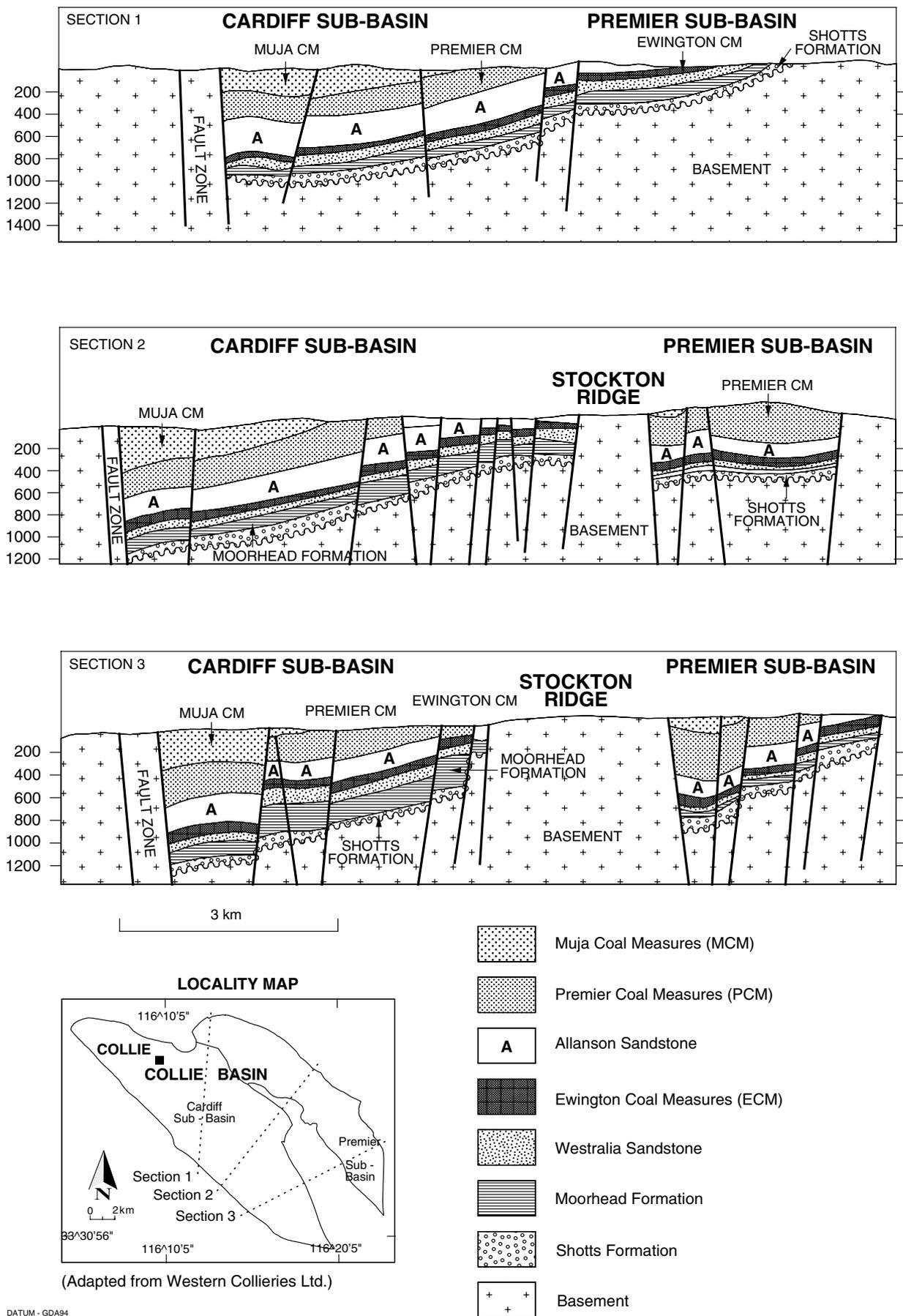


Figure 3. Stratigraphic sections

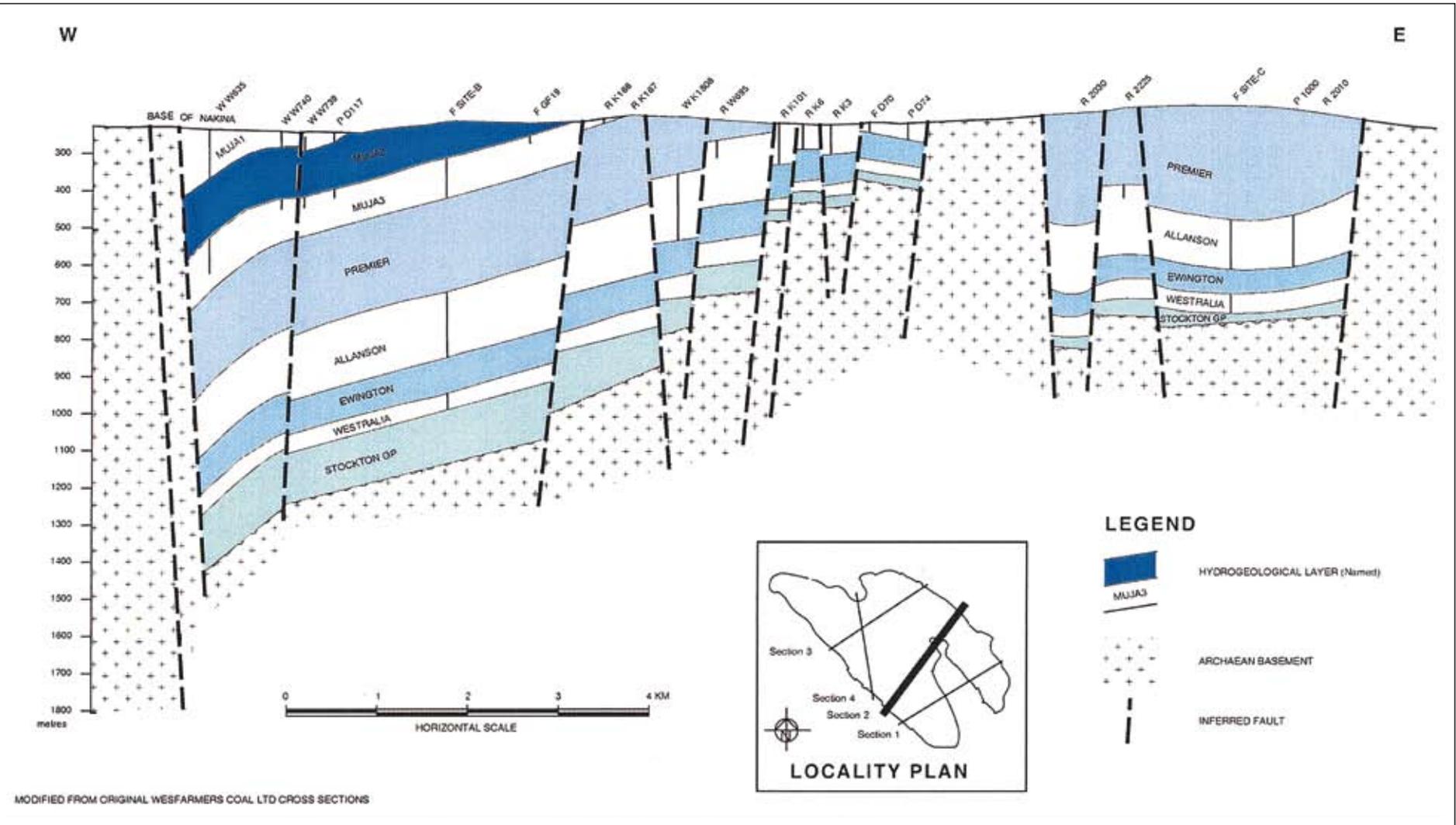


Figure 4. Revised geological section

separated by aquitards typically 2-5 m thick consisting of shale/ coal/siltstone /mudstone and minor sandstone layers having low permeability. The sandstone is generally poorly sorted, with grain sizes from fine to coarse, and arkosic (Le Blanc Smith, 1993). Cementation is highly variable, ranging from unconsolidated sands to highly competent sandstones (AGC, 1978). Apart from numerous layers of interbedded clay and coal that separate the sandstone sequences into numerous thin aquifers, the sandstone aquifers themselves are likely to possess considerable vertical anisotropy due to variation in grain size and other properties with depth. The silt or clay content of the sand varies from nil to very high. The coarse-grained beds can include a large proportion of interstitial white clay (AGC, 1978).

Despite the sharp local variations in properties, the regional hydraulic properties of the sandstones, as determined from pumping tests, show a high level of consistency.

#### 2.3.3.2 Aquitards

The coal measures mostly have stacked upward-fining cycles that are frequently coal capped, and subordinate upward-coarsening cycles (Le Blanc Smith, 1993). In the unfaulted state, the mudstone/shale/coal beds are expected to be strong barriers to vertical groundwater movement. This is indicated by significant head differences between adjoining aquifer intervals (Western Collieries, 1991). However, leakage effects have been observed in pump tests at the Cardiff-South production wellfield in the Cardiff Sub-basin (AGC, 1981) and in Muja opencut dewatering bores (Groundwater Resource Consultants, 1984). Western Collieries (1991) reported that aquitard layers are sometimes transmissive and can allow significant vertical leakage under a vertical head gradient. It is most likely that this interconnection exists only in areas where the shale lenses pinch out or are breached, for example by faulting (AGC, 1985). Vertical leakage can therefore be expected to be higher in heavily faulted zones near the margins of the basin.

#### 2.3.4 Nakina Formation and surficial sediments

The Nakina Formation is regarded as a flat lying aquifer, with groundwater flow and occurrence controlled by topography, seasonal climatic influences, and lithology. The Nakina Formation is in hydraulic connection with the subcropping Permian strata.

Western Collieries (1991) also note that:

*'In a pristine setting, prior to population and the occurrence of coal mining and power station activities, the sediment profile was probably saturated to elevations at which the aquifer systems were, at least seasonally, effluent into some of the surface drainage courses.'*

The watertable map produced in Varma (2002, Figure 10) is made up of water levels in the Nakina Formation, as well as underlying subcrop units in areas where the Nakina Formation is unsaturated. The saturated thickness of Nakina Formation is shown in Varma (2002, Figure 9).

## 2.4 Groundwater age and confinement

CSIRO Land and Water (1999) studied groundwater residence times in the northern part of the Premier Sub-basin using carbon-14 activity and CFC-12 concentrations. CSIRO found that the groundwater samples were a mixture of 'young' (less than 50 years, indicated by the presence of CFC-12) and 'old' groundwater, but for deeper groundwater samples the proportions of young water were small (<5%) or non-existent. Groundwater ages up to 17 500 years were determined in deeper aquifers, indicating a high groundwater residence time in the natural state and a slow rate of movement in the deep aquifers. This implies that aquitards may isolate the deep groundwater from the shallow groundwater system, such that the sustainable yield for deep aquifers may be less than the rate of rainfall recharge to the shallow groundwater.

There is no record of groundwater heads in the Collie Group aquifers prior to the development of mining, dewatering and groundwater abstraction. It is likely that vertical hydraulic gradients in the natural state would have been low because the basin is surrounded by basement rocks and the natural drainage into and out of the deep sediments would be low. It is likely that the old groundwater age in the deep aquifers may be as much a result of the low rate of drainage out of these sediments as of the hydraulic confinement provided by the overlying shale/coal/mudstone aquitards. Mine dewatering and groundwater abstraction by bores would greatly increase the vertical hydraulic gradients and would likely induce substantial vertical leakage, mainly where faulting has occurred and where the deeper aquifers subcrop beneath the Nakina Formation. The vertical leakage in some areas would be further increased by the removal of aquitards by coal mining and possibly by fracturing of aquitards above underground mines by subsidence.

## 2.5 Hydraulic properties of aquifers

Table 3 summarises transmissivity, hydraulic conductivity and storage coefficient values given in the literature for the various aquifers. Values of hydraulic conductivity have been determined by three methods: pumping test, slug test and grain size analysis. The most reliable values are from pumping tests, as these are performed over a longer time period than other tests.

The table shows uniformity in aquifer hydraulic conductivity throughout the basin, with a mean horizontal hydraulic conductivity for the aquifers of 3 m/d. Apparent variations shown by the table with depth and with location are probably more related to statistical scatter than true regional change. Most storage coefficient values are in the range  $10^{-5}$  to  $10^{-3}$ , corresponding to confined to semi-confined conditions.

Dames and Moore (1998) adopted the following hydraulic values in developing a model for the Premier Coal Measures in the Ewington area:

Horizontal K for aquifers:	5-6 m/d
Storage coefficient for aquifers:	$10^{-6}$
Vertical K for aquitards:	$10^{-3}$ m/d

Table 3. Summary of hydraulic parameters determined by pumping tests

Sub-basin	Mean model layer	Layer name	Horizontal hydraulic conductivity (m/d)				Storage coefficient			
			N	Min. value	Max. value	Avg. value	N	Min. value	Max. value	Avg. value*
Cardiff	2	Muja 1	7	0.3	1.6	0.7	1	9E-02	9E-02	9E-02
	3	Muja 2	5	1.4	5.0	3.5	2	3E-04	5E-04	4E-04
	4	Muja 3	7	0.2	4.5	1.9	5	8E-05	2E-03	3E-04
	5	Premier	2	1.9	2.6	2.3	2	3E-04	4E-04	4E-04
	6	Allanson	3	3.5	8.6	5.7	3	3E-04	6E-04	4E-04
	7	Ewington	3	1.7	5.4	3.2	2	6E-04	3E-03	1E-03
Cardiff Summary			27	0.2	8.6	2.5	15	8E-05	9E-02	6E-04
Premier	4	Muja 3	4	1.0	6.5	3.5	4	5E-05	3E-04	1E-04
	5	Premier	7	1.1	7.7	4.0	7	2E-04	3E-04	3E-04
	7	Ewington	1	4.8	4.8	4.8	1	9E-04	9E-04	9E-04
Premier Summary			12	1.0	7.7	3.9	12	5E-05	9E-04	2E-04
Collie Basin Summary			39	0.2	8.6	2.9	27	5E-05	9E-02	4E-04

\*Logarithmic average of Storage Coefficient values

N: Number of readings

There is scarce information on the hydraulic properties in the Nakina Formation. The only estimate of hydraulic conductivity is 5.9 m/d near Long Pool based on grain size analysis (Henderson, 1999).

## 2.6 Important aspects of mining

### 2.6.1 General

Some of the mine details in this section have been taken from Report No. 156, Western Collieries (1991). The information reproduced below has been cleared for publication by Wesfarmers Coal (Geo-Eng, 2000).

### 2.6.2 Underground mines

The areas which have been subjected to underground and open cut mining in the past are shown in Figure 1. Underground mining commenced in the Collie Basin in the 1890s, and ceased in 1994 (Dave Chapman, Pers. Comm.). The most significant underground mines in relation to the Collie River South Branch are Western 2, Western 6, and Western 7. The key features of these mines are described below.

Western 2 and Western 6: These mines exploited the Wyvern Seam that is 3-4 m thick at this location, and subcrops below 10-20 m of Nakina Formation. The Permian strata have a NW strike, and dip at 4° to 5° to the SW. Mining commenced near the seam

subcrop, and extended to 2500 m down-dip, with maximum thicknesses of cover of around 210 m. The McAlinden Fault marks the down-dip limit to the mining.

Western 7: This mine exploited the Collieburn No. 2 Seam, which is approximately 2.5 m in average thickness where mined. Mining commenced near the seam subcrop, and extended 1400 m down-dip (to Dec. 1991), with maximum depths of cover of 100 m. Until 1991, development had not been limited by faults or other geological constraints.

The Western 2, Western 6, and Western 7 mine voids are considered to be currently in a state where they would be full of water, rather than partially collapsed or backfilled, although some sections of Western 2 were allowed to partially collapse for trial purposes. Several of the ACIRL production bores draw water directly from the Western 6 underground mine void.

Underground mining in some areas may have caused subsidence of overlying strata that has the potential of affecting the hydraulic properties of the strata. However, it is assumed that such effects are localised and not relevant to the regional scale Collie Basin groundwater flow model.

### 2.6.3 Open cut mines

The mines of the Cardiff Sub-basin are identified as WO5B, WO5C, WO5D, WO5F, N9, WO5H (formerly WO3). These mines exploited seams of the upper part of the Muja Coal Measures, with the exception of WO5D which exploited the Wyvern Seam in the lower part, and the WO5H which exploits coal seams of the Ewington Coal Measures.

The open cut mines within the Premier Sub-basin include the Muja, Chicken Creek, Premier 1, Premier 4, and Ewington II deposits. These mines exploit coal of the Premier Coal Measures, and to a lesser extent, the Muja Coal Measures.

## 3 Development of the numerical model

### 3.1 General

The Collie Basin is geologically and hydrogeologically complex, containing numerous alternating aquifer/aquitard layers that have been folded and complexly faulted. The conceptual model seeks to simplify this complex geology and hydrogeology, whilst maintaining the complex features necessary to allow a realistic representation.

The Collie Basin Groundwater Model is a regional scale model covering both the Cardiff Sub-basin and the Premier Sub-basin. As such, much of the model input is at a scale that is suitable for representation of regional features. However, it is also important to consider the current objectives of the model, which include representation of surface water-groundwater interaction at pools along the South Branch and the East Branch of the Collie River that have been identified as being significant by the Collie Water Advisory Group (CWAG, 1996). The model also needs to include open cut mine voids in order to study the impacts of mine management programs on the surrounding groundwater. The location of the pools and mine voids is shown in Figure 1.

### 3.2 Selection of a suitable modelling package

In selecting a preferred groundwater modelling package, a number of options were considered taking into account the objectives and end-use of the model. The following points were important in selecting the modelling package.

**Spatial discretisation:** A finite element grid may be more efficient in defining the detail necessary around the Collie River South Branch pools. A finite difference grid could also define the necessary detail, but the number of cells required would be significantly greater, as there would be a number of inactive cells.

**Ability to model surface water-groundwater interaction:** The basic MODFLOW package cannot handle unsaturated conditions satisfactorily, but MODFLOW-SURFACT allows modelling of unsaturated conditions, seepage faces, and drying/re-wetting processes.

**Complexity of the hydrogeology, including the effects of faulting on vertical and horizontal groundwater movement:** Most of the layers subcrop beneath the Nakina Formation (Figure 2). This means that the hydrogeological conditions of the model layers will vary between confined and unconfined conditions, and may also vary between being saturated and unsaturated. In some areas the Nakina Formation is unsaturated, and the watertable is present in the underlying Permian sediments. The model chosen needs to be able to simulate these conditions without significant error.

**Re-wettability of cells:** Dewatering in the basin has caused aquifers to be unsaturated in places, for example, the Nakina Formation is unsaturated in many areas. Cessation of mining will cause water levels in the basin to recover. This will give rise to model cells being initially dried out and subsequently re-wetted.

**Solute transport:** Solute transport modelling may be a requirement of later model stages, so any package selected should be capable of solute transport modelling. The ability to simulate variable density flow is also regarded as desirable.

**User-friendliness:** An important consideration is the ease of use and minimum training requirement for operating a complex model. In this regard, MODFLOW is seen as an industry standard, and considerable technical support exists for MODFLOW.

**Applications:** It is considered that an important aspect of modelling is the ability to readily understand, interpret and defend the model output. As MODFLOW is a simple and widely understood package, and many different applications have been reported, interpretation of the model output can be undertaken with confidence. On the other hand, less widely used FEM packages may claim to be able to model certain conditions, but the packages may not have been rigorously tested, and applications of the packages may not be reported. As such, interpretation of modelling results is less likely to be undertaken with confidence.

**Water balance simulation:** It is considered that accurate simulation of the water balance of pools and mine voids is fundamentally important for this model. As such, a package that can simulate total water balance is desirable. SURFACT 2000 is able to perform integrated surface water-groundwater modelling, including overland flow and unsaturated flow.

**Automatic calibration:** A range of calibration packages is desirable to automate the calibration process. This may be achievable through model independent calibration programs such as UCODE and PEST, or newly released codes such as MODFLOW 2000.

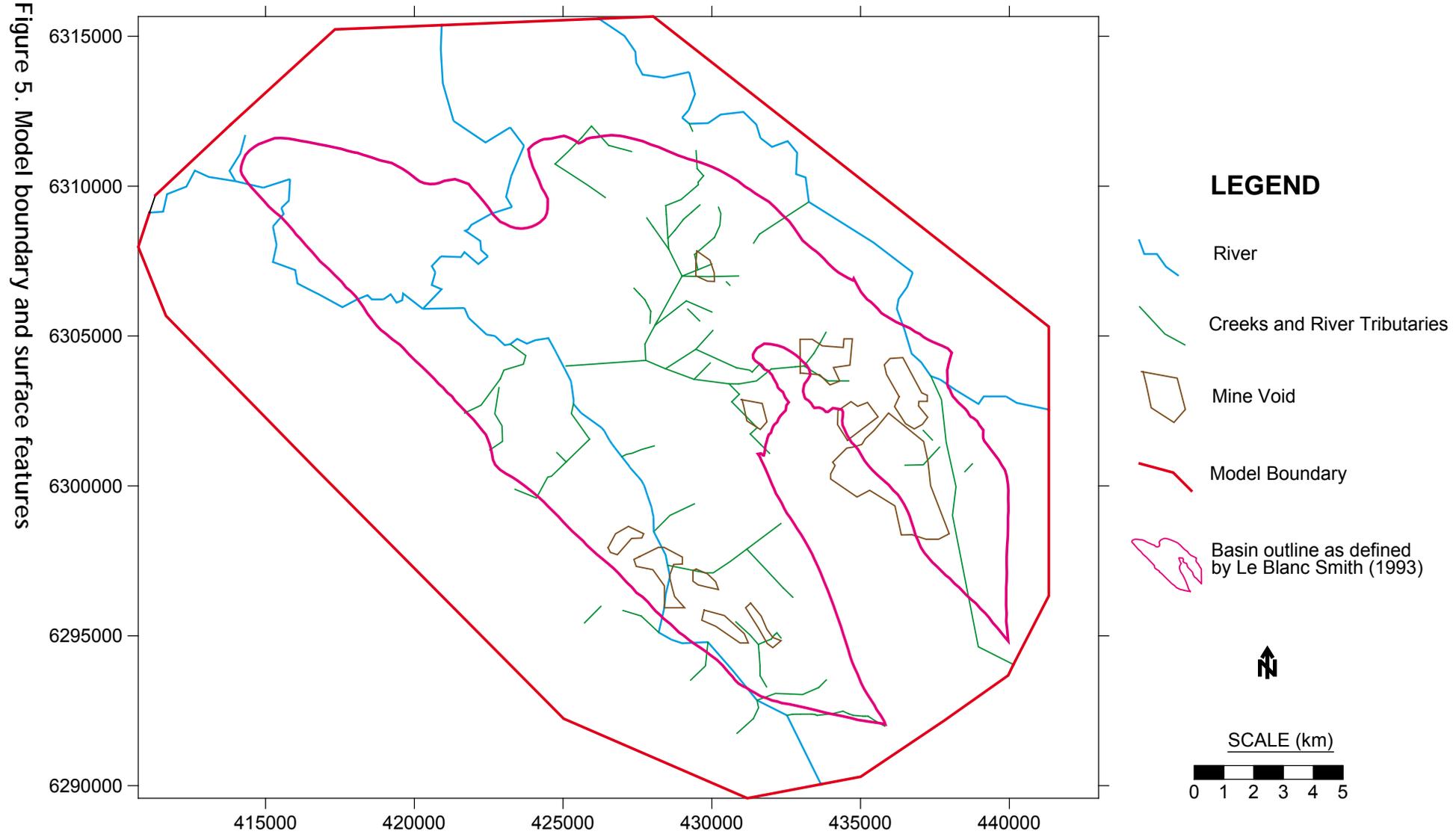
The recommended model for this project is MODFLOW. GMS is recommended as the data input, manipulation and presentation package because of its state of the art features and user friendliness. GMS can import base maps as TIFF and DXF files, as well as GIS data from ArcView and ARCINFO, and can generate cross-sections and fence diagrams at any location in the model.

MODFLOW-SURFACT 2000 could have been used if available, as the stated capabilities of the package would be useful for the surface water-groundwater interaction and water balance considerations of this project. However, MODFLOW-SURFACT 2000 is not supported by GMS, and for modelling a geology as complex as the Collie Basin, it would be difficult to achieve this on any other platform apart from GMS.

### 3.3 Model domain

The boundary of the model is shown in Figure 5. The northeastern and southwestern boundaries were chosen to coincide with exposed bedrock ridges, where a groundwater divide is present.

The location of model boundaries in other areas is considered to be far enough from areas of interest (eg the Collie River South Branch) such that the boundary effects will



be negated. The model domain is 534 km<sup>2</sup> in surface area. The area of the Collie Basin within the model domain is 225 km<sup>2</sup>, and the area outside the Collie Basin is 309 km<sup>2</sup>. The main surface features that have been defined in the model include rivers, creeks, mines, wellfields and river pools.

### 3.4 Boundary conditions

The entire model boundary is modeled as a no-flow boundary. The northeastern and southwestern boundaries of the model represent natural no-flow boundaries. They are located, where possible, along groundwater divides represented by topographical ridgelines.

In other areas, such as the southern and northwestern boundaries where the Collie River South Branch enters and exits the model domain, the boundary is also modeled as a no-flow boundary. This boundary condition was selected as the boundary is located in the bedrock outside the basin and groundwater flow across the boundary is believed to be minor. Since the southern and northwestern model boundaries are several kilometres away from the basin margin (Figure 5), the no-flow boundary condition in these areas does not restrict water flow across the basin margin. Under the current boundary condition, groundwater discharges from the basin to rivers and creeks and by evaporation in areas of shallow watertable.

### 3.5 Model layers

#### 3.5.1 General

The aquifer/aquitard sequence of the Collie Basin is repetitive and complex. Much of the Permian sequence comprises stacked aquifer/aquitard cycles, which have been vertically offset by numerous faults. It would not be possible (or desirable) to represent all separate sandstone/shale/coal sequences due to both the complexity of the task, the lack of data available to undertake it, and large computation time required. Therefore assumptions were made to simplify the model.

The hydrostratigraphic subdivision for the model is based on the generalised lithostratigraphy presented in Le Blanc Smith (1993) and the hydrostratigraphy presented in Varma (2002). Further subdivision has been made for the Muja Coal Measures taking into account large vertical head gradients.

Aquaterra (1999) recommended a seven-layer model for the basin. This has been further refined to a model represented by 10 layers (Table 4). In general, the conceptual model put forward by Aquaterra is regarded as sound in the context of model layering. However, additional layers have been added to the base of the sequence to allow representation of aquifers lower in the sequence. The surfaces of each of the layers, their extent and thickness, are shown in Plates 1–19 in Appendix C.

Table 4. Correlation of model layers

Model layer	Stratigraphic Unit	Coal Seams	
		Cardiff Sub-basin	Premier Sub-basin
1		<b>Nakina+surficial</b>	
2	<b>Muja 1</b>	Cardiff A Cardiff 1 Cardiff 2 Minos Cardiff Neath Abe L Ben	Ate Bellona Ceres Eos Galatea
3	<b>Muja 2</b>	Collieburn Upsilon Alpha	Hebe
4	<b>Muja 3</b>	Wyvern Rhea Collieburn 2 Phoenix	Hebe Premier, Premier 1, Apis
5	<b>Premier Coal Measures</b>	Hermes Acis Circle Icarus Griffin Echo Tantalus Venus	Cardiff 1 Premier 2, Uraeus Premier 4 Upper Premier 4, 5a,5b,5c, Pegasus Premier 6, Juno Upper, Braireus, Gryps Juno Lower, Chiron Leda Premier7, Tethys Upper & Lower, Centaur
6	<b>Allanson Sandstone</b>	Hymen	Hymen
7	<b>Ewington Coal Measures</b>	Ewington 1A Ewington 1L Iris Ewington 2 Moir Stockton Wallsend	Ewington 2, 3 unnamed seams Moir Stockton Wallsend, Achilles Ajax, Ares
8		<b>Westralia</b>	
9		<b>Stockton Group</b>	
10		<b>Basement (Pre-cambrian Crystalline Rock)</b>	

The base of one layer is the top of the underlying layer, so the elevation of all surfaces from surface to basement has been determined. The model layers are discussed in more detail below.

**Layer 1 – Nakina Formation and surficial sediments:** The Nakina Formation and the surficial sediments together form an unconfined aquifer covering the entire model area, and is the only layer that can be considered as being generally flat lying. The reduced level of the base of Layer 1 representing the Nakina Formation and the surficial sediments is shown in Plate 2 and the extent and thickness of Layer 1 is shown in Plate 3.

**Layers 2, 3 and 4 – Muja Coal Measures:** The subcrop of Muja Coal Measures beneath the Nakina Formation has the maximum areal extent in the Cardiff Sub-basin. The unit subcrops beneath the significant pools of the Collie River South Branch. In addition, much of the mining and groundwater abstraction in the Cardiff Sub-basin has occurred from the Muja Coal Measures. The layers defined in the Muja Coal Measures are the same as those recommended by Aquaterra (1999), except that they have been extended to their lateral equivalents in the Premier Sub-basin. The layers are described below.

**Layer 2 – Muja 1:** The Muja 1 model layer extends from the base of Nakina Formation to the Ben Seam in the Cardiff Sub-basin, and the Galatea Seam in the Premier Sub-basin. In the Cardiff Sub-basin this layer includes the WO5 open cut mine voids (with the exception of WO5D and WO5H). The reduced level of the base of Muja 1 is shown in Plate 4, and the contours of thickness of the unit are shown as Plate 5.

**Layer 3 – Muja 2:** The Muja 2 unit extends from the Ben Seam to the Alpha Seam in the Cardiff Sub-basin, and the Galatea to the Hebe Seam in the Premier Sub-basin. In the Cardiff Sub-basin the unit has not been mined, but groundwater abstraction has occurred from this layer to facilitate underground mining in the underlying layer. The reduced level of the base of Muja 2 is shown in Plate 6, and the contours of thickness of the unit are shown in Plate 7.

**Layer 4 – Muja 3:** The Muja 3 unit extends from the Alpha to the Phoenix Seams in the Cardiff Sub-basin, and from the Hebe to the Premier 0 Upper/Premier 1/Apis Seam in the Premier Sub-basin. In the Cardiff Sub-basin, underground mining from the Western 2, Western 6, and Western 7 mines, and open-cut mining from the WO5D mine has occurred from this layer. In the Premier Sub-basin, the bottom of Muja Mine is in the Hebe Seam immediately above the Premier Coal Measures. The contours of the reduced level of the base of Muja 3 are shown in Plate 8, and contours of the thickness of the unit is shown in Plate 9.

**Layer 5 – Premier Coal Measures:** The Premier Coal Measures is modeled as a single layer. The unit has not been recently mined in the Cardiff Sub-Basin, but mining from this layer in the Premier Sub-basin is continuing. Groundwater abstraction for power station supply occurs from the Premier Coal Measures in both sub-basins at the Cardiff South and Shotts wellfields. The reduced level of the base of Premier Coal Measures is shown in Plate 10, and the thickness of the

unit is shown in Plate 11.

**Layer 6 – Allanson Sandstone:** This layer is formed by the Allanson Sandstone that is not coal bearing and hence has not been mined; however, groundwater abstraction from this layer takes place at Cardiff South and Shotts wellfields for power station supply. The reduced level of the base of Allanson Sandstone is shown in Plate 12, and the thickness of the unit is shown in Plate 13.

**Layer 7 – Ewington Coal Measures:** This layer is formed by the Ewington Coal Measures that is mined at the WO5H open cut mine in the Cardiff Sub-basin. Pumping for power station water supply occurs from this layer in both sub-basins. The reduced level of the base of Ewington Coal Measures is shown in Plate 14, and the thickness of the unit is shown in Plate 15.

**Layer 8 – Westralia Sandstone:** This layer is formed by the Westralia Sandstone. Abstraction for power station supply occurs from this layer at Cardiff South wellfield. The reduced level of the base of Westralia Sandstone is shown in Plate 16, and the thickness is shown in Plate 17.

**Layer 9 – Stockton Group:** The Stockton layer is formed by the Stockton Group sediments and consists of the Moorhead Formation and the Shotts Formation. The reduced level of the base of Stockton Group is shown in Plate 18, and the thickness of the unit is shown in Plate 19.

**Layer 10 – Basement:** There is insignificant groundwater flow in the Archaean granitic basement rocks. As such, the basement has been included as a model layer to allow minor groundwater flow in the area outside the basin.

### 3.5.2 Representation of model layers

Using the surface elevations of the ten model layers, a three-dimensional geological model was created in GMS to visualise the entire model domain. This solid model shows the correlation of all hydrostratigraphic units in 3D and areas where Layers 2 to 9 subcrop below the Nakina Formation (Layer 1).

A cross-section through the GMS Solid Model and a fence diagram generated from the Solid Model are shown in Figures 6 and 7. The boundaries of each layer and areas where the layers subcrop are simulated in the numerical model on the basis of the solid model.

The ten units shown in Figure 6 are simulated in the numerical model with each unit representing one model layer. The layers are represented in MODFLOW as 'true layer type,' where the real top and bottom elevations of hydrostratigraphic units are represented by model layers.

In areas where the unit is absent, however, the corresponding model layer must not terminate because MODFLOW requires that model layers must continue throughout the model domain. In this case, the model layer that represents the hydrostratigraphic unit has been continued as a 'dummy' layer, and the 'dummy' layers have been given the same hydraulic properties as the units immediately below them. The dummy layer thickness has been made as thin as possible to represent the actual hydrogeological

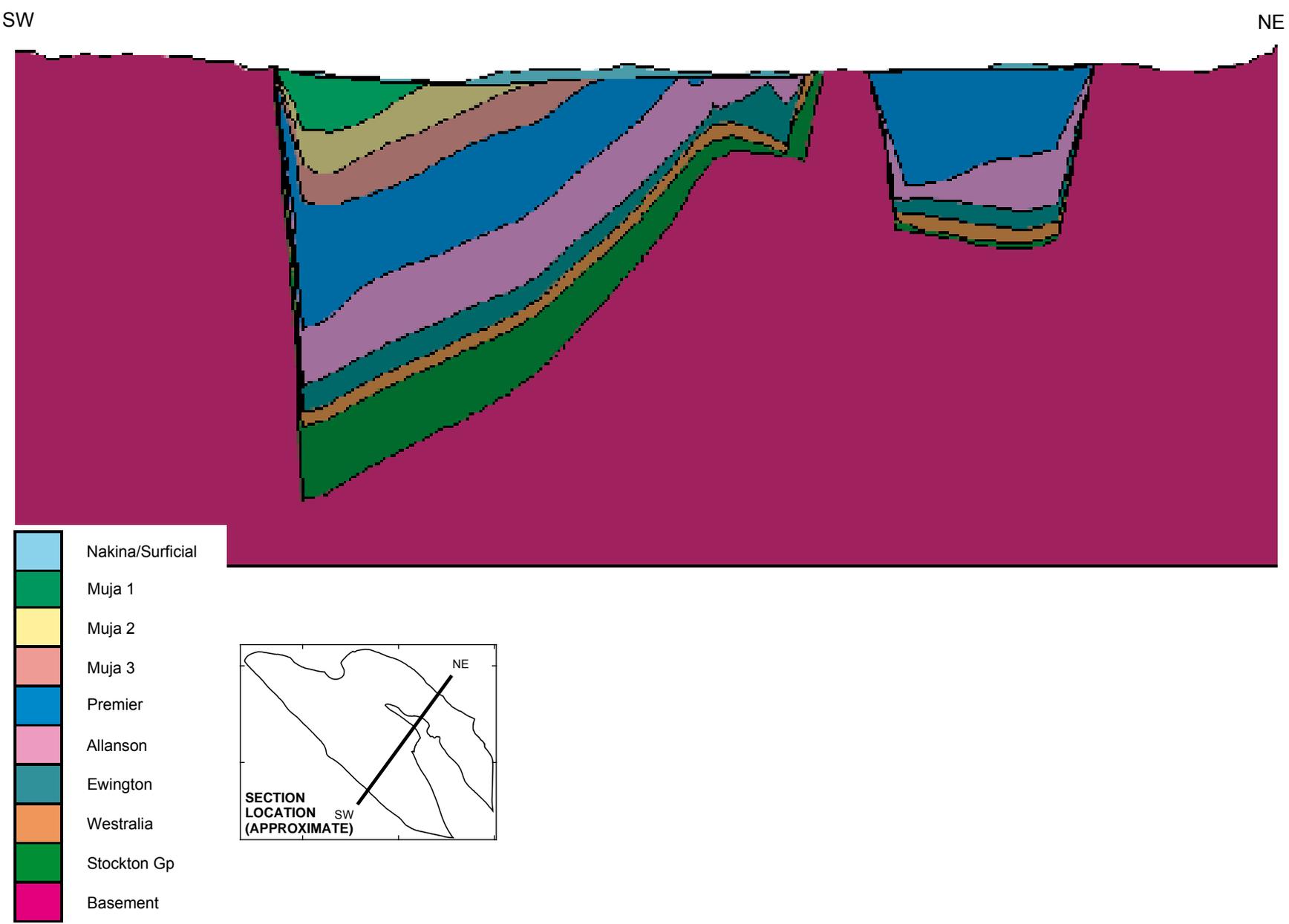


Figure 6. Model cross-section

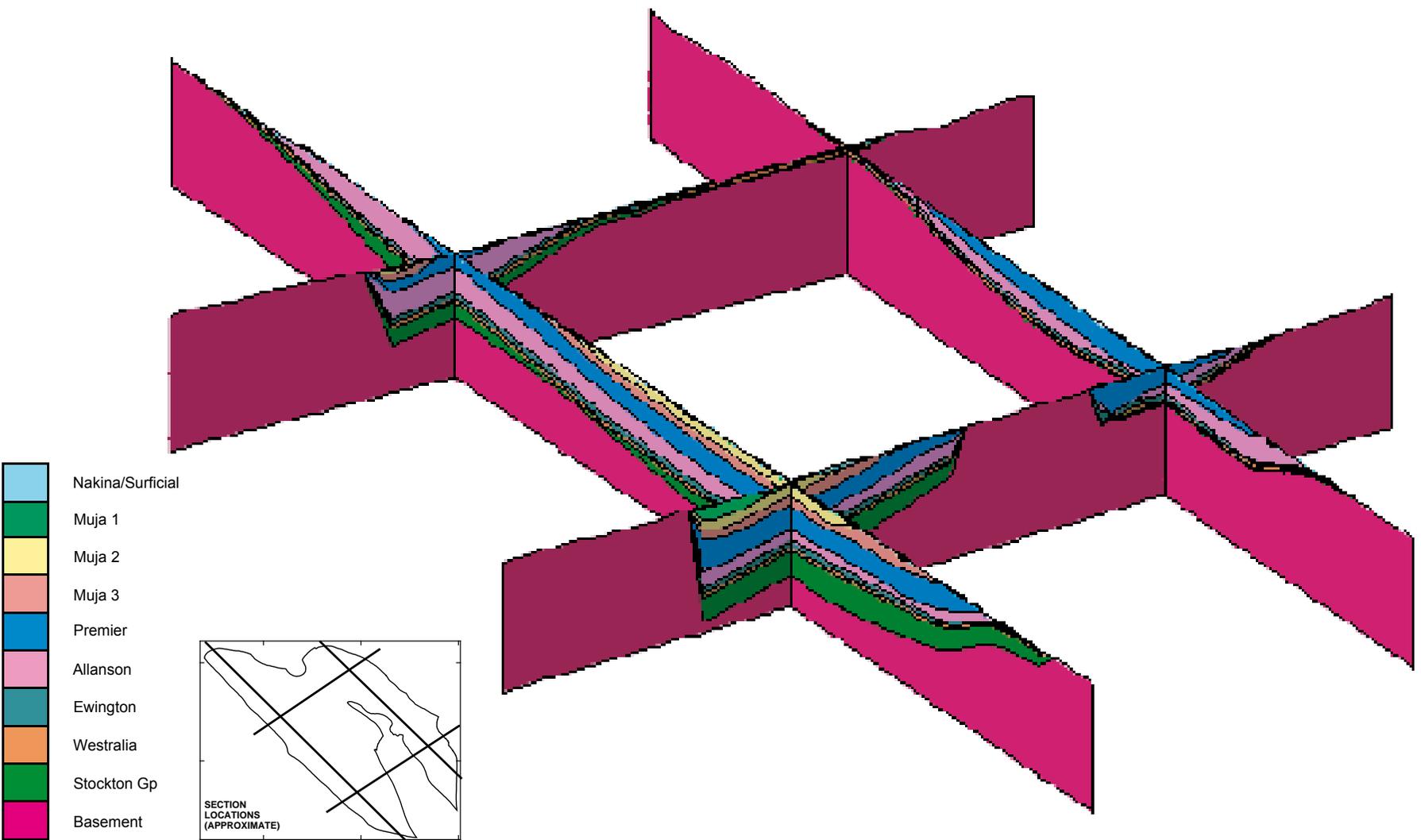


Figure 7. Model fence diagram

conditions, at the same time maintaining numerical stability. In general the thickness of dummy layers is restricted to 3 to 5 m.

### 3.5.3 Simulation of vertical leakage between hydrostratigraphic units

In MODFLOW, water exchange between hydrostratigraphic units is simulated by vertical leakance, which is a function of the vertical conductivity and the head difference in the layers. In areas where a hydrostratigraphic unit subcrops beneath the Nakina Formation, vertical leakage between the Nakina Formation and the underlying subcrop area is simulated as an indirect leakage across dummy cells. This approach is illustrated in Figure 8.

In addition, in order to represent the model layers as discrete strata bounded by coal seams acting as aquitards, horizontal flow barriers (HFB) were introduced to restrict such horizontal flow from the 'dummy' part of the model layer into the 'actual' strata. The hydraulic property of the HFB is equivalent to the vertical hydraulic conductivity of the model layer. This approach represents the model layer in the areas of subcrop beneath the Nakina Formation more accurately. Such an approach avoids inaccuracies in water balance of individual layers arising from horizontal flows from the 'dummy' part of the model layers that actually 'underlies' the layer in stratigraphic sequence, and any exchange of groundwater between the layers should actually be dependent on vertical hydraulic conductivity rather than horizontal conductivity.

## 3.6 Model grid

The model grid presented in Aquaterra (1999) on the conceptual model is considered generally suitable. The model grid is aligned along the long axis of the Collie Basin ie with a NW-SE orientation. This would align the model grid with the long axis of the basin, the general direction of flow of the Collie River South Branch (in the area of consideration), and the strike direction of major faults.

The grid cell size is an important consideration, and it is a general recommendation that the total number of cells in the model does not exceed 400 000. However, it is more efficient to keep the total number of cells below 200 000.

Figure 9 shows the model grid, including detail in the area around the South Branch pools. The model grid has been made finer in areas of significance, eg river pools and mine voids, and relatively coarse in other areas. A minimum grid size of 50 × 100 m was used to represent the Collie River South Branch pools. The grid size increases gradually from the river cells by 10% in both row and column direction to a maximum grid size of 400 × 400 metres in the marginal and non-critical areas of the model. The total number of cells in each layer is 13 624 (104 × 131).

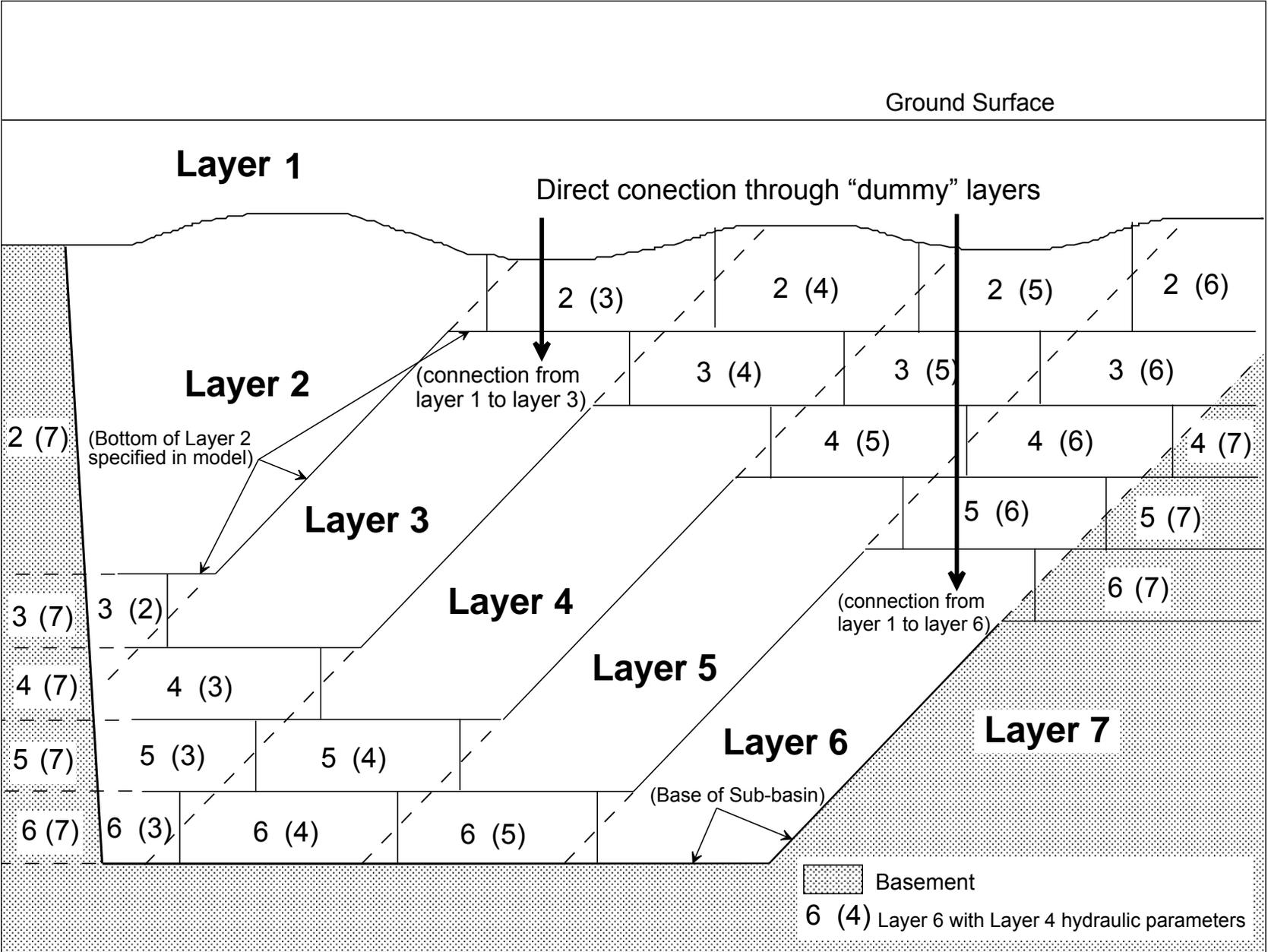
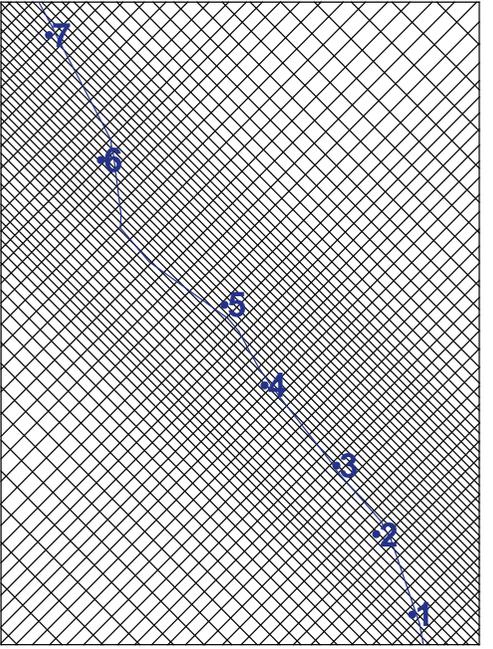


Figure 8. Use of dummy layers (Aquaterra, 1999)



Grid detail around Collie River south branch pools

**LEGEND**

-  River
-  Some creeks and river tributaries
-  1 Pool

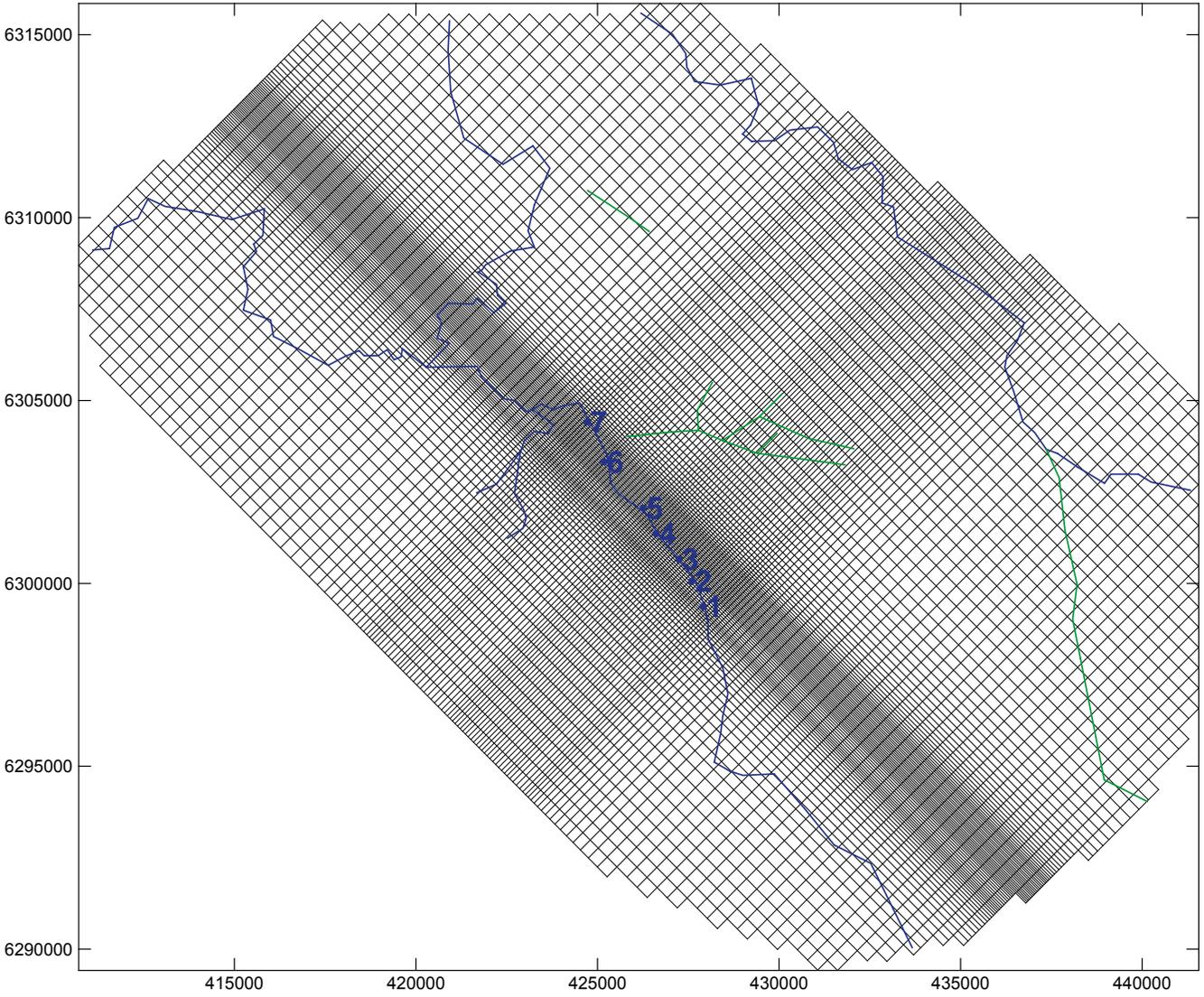


Figure 9. Model grid

## 3.7 Layer type and property

Model Layer 1 is defined as an unconfined aquifer. Model Layer 10 (basement) is defined as a confined aquifer. All the other layers are defined as confined/unconfined aquifers with variable transmissivity (Layer Type '3' in MODFLOW). This model layer type is appropriate for the Collie Basin since the watertable occurs in several model layers in their respective areas of subcrop beneath the Nakina Formation. This model layer type also enables the model layer to be unconfined in some areas and confined in other areas. Model layer of Type '3' can be computationally expensive, however, as the transmissivity is updated for each time step and is therefore considered as more realistic.

Input parameters include horizontal hydraulic conductivity ( $K_h$ ), vertical hydraulic conductivity ( $K_z$ ), specific storage ( $S_s$ ), and specific yield ( $S_y$ ). The vertical hydraulic conductivity ( $K_z$ ) is utilised in MODFLOW as a component of VCONT, which is a function of the  $K_z$  and the thickness of the layer (Anderson & Woessner, 1991). The initial values of hydraulic properties for model calibration were taken from Table 3 determined as a part of Stage I work. Hydraulic conductivities for the Model Layers 3 to 9 have been divided into several zones based on the depths below ground surface. Smaller hydraulic conductivities were assigned to the zones of greater depth. This approach ensured that maximum groundwater flux was in the shallow areas of the model layers, and flow velocity in the deeper parts were significantly reduced consistent with the conceptual understanding of flow in the deeper parts of the basin as indicated by groundwater age studies (CSIRO, 1999).

## 3.8 Rainfall recharge and discharge

### 3.8.1 General

The major source of groundwater recharge to the Collie Basin is considered to be rainfall infiltration. Only a small amount of groundwater recharge is believed to be from other sources, such as streams, discharge from mine dewatering and flow from outside the basin margin. A small volume of groundwater from topographical highs in the granitic areas outside the basin may flow towards the basin and cross the basin margin, however this flow is expected to be insignificant as the bedrock has low permeability and the flow velocity is likely to be small.

Prior to any mining or any major groundwater abstraction in the basin, it is considered that shallow groundwater flow was from topographically elevated areas towards rivers and creeks within the basin. The configuration of the watertable is therefore sub-parallel to the topography. Conceptually, groundwater discharge occurs as baseflow to the Collie River and its tributaries and by evapotranspiration from wetlands and other areas of shallow watertable.

### 3.8.2 Representation of recharge and discharge in the model

Rainfall that infiltrates the ground surface and reaches the watertable is termed net groundwater recharge. The spatial distribution of the net rainfall recharge depends upon

many factors, such as rain intensity, surficial soil types, vegetation types and the depth to the watertable.

During Stage I it was identified that a key component of the modelling process would be the use of vegetation cover maps to generate spatially distributed estimates of recharge. However, information regarding the LAI (leaf area index) of the Collie Basin that could be used to produce estimates of groundwater recharge via a simple parametric water balance model, did not exist and so this methodology of estimating groundwater recharge could not be adopted. Moncrieff (1993) noted that groundwater recharge is enhanced by a decrease in evapotranspiration from areas where the watertable has been lowered by groundwater abstraction. Based on this observation, it was broadly assumed that the net rainfall recharge is greatest in areas where the watertable is deep and least where the watertable is shallow. Influence of surficial soil type was not considered at this stage. This method of discretisation of recharge in the model is approximate and will need to be refined in future when more data is available.

### 3.8.3 Recharge zones

The total recharge of approximately 20 GL/yr (Varma, 2002) taking place in the basin has been discretised into several zones based on depth to the steady state watertable. Thirty-eight recharge zones (Table 4) have been defined for the entire model domain. These zones are based on the topography and the depth to the conceptual steady state watertable (Figure 16). In defining recharge, three different groups of recharge zones are identified.

Zones outside basin margin: The rainfall recharge zones 1, 2, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21 are mostly outside the Collie Basin margin. The recharge rates are relatively small for these zones (in the order of  $10^{-5}$  m/day) due to the low permeability of bedrock. The total rainfall recharge to these zones has been adjusted in order to produce a satisfactory watertable configuration in the bedrock areas. Total recharge applied to these zones is about 2.6 GL/year. Conceptually, it is considered that most of this recharge eventually enters the basin as baseflow in the streams that originate outside the basin.

Zones with intermediate watertable depths (5–10 m) within the basin: It is considered that in these areas a relatively high evapotranspiration (ET) applies and consequently results in a lower net rainfall recharge than that in other areas with deeper watertable. These include mostly zone 29 having a recharge rate of  $2.5 \times 10^{-4}$  m/day.

Zones with deeper watertable (>10 m) within the basin: These zones have a relatively high recharge value due to their reduced ET rate, and include zones 26, 30, 31, 34, 35, 36 and 38. The recharge rate in these zones is between  $1.3 - 3.3 \times 10^{-4}$  m/day.

### 3.8.4 Discharge zones

Groundwater discharge areas in the model include river valleys, creeks, wetlands and areas with a watertable depth less than 5 m. In these areas, a net rainfall recharge of zero is applied. These zones include Zones 3, 8, 12, 24, 27, 32 and 37 (Table 5,



Figure 10. Model recharge zones

Figure 10). These zones are located in river valleys, creeks and wetlands, where groundwater discharges. The Collie River valley is represented by Zones 3, 8, 12 and 27. Zone 37 is an area of shallow watertable, where water leaves the system mainly via evaporation and forms an additional groundwater discharge zone. At these discharge areas and other topographically low areas (that have not been defined as zones of zero recharge), an evapotranspiration (EVT) condition has been introduced to account for groundwater discharge by a relatively high evaporation. The evapotranspiration rate was adjusted during steady state model calibration so that these topographically low areas are not flooded.

Table 5. Rainfall recharge applied to the model

Zone	Area (km <sup>2</sup> )	Rainfall recharge rate (m/d)	Annual recharge (GL/year)	Zone	Area (km <sup>2</sup> )	Rainfall recharge rate (m/d)	Annual recharge (GL/year)
1	62.7	2.0E-05	4.6E-01	20	7.1	1.0E-05	2.6E-02
2	65.3	3.8E-05	9.1E-01	21	18.4	5.0E-05	3.4E-01
3	8.6	0	0	22	8.5	0	0
4	9.5	2.5E-05	8.7E-02	23	2.2	0	0
5	7.5	1.4E-04	3.8E-01	24	3.4	0	0
6	23.8	4.0E-05	3.5E-01	25	15.2	4.9E-04	2.7E+00
7	8.1	1.0E-05	3.0E-02	26	17.5	3.3E-04	2.1E+00
8	8.7	0	0	27	11.2	0	0
9	10	0	0	28	1.8	0	0
10	14.5	3.0E-05	1.6E-01	29	43.8	2.5E-04	4.0E+00
11	3.6	1.0E-05	1.3E-02	30	2.9	2.0E-04	2.1E-01
12	40.1	0	0	31	5.6	3.0E-04	6.1E-01
13	3.2	2.0E-05	2.3E-02	32	15.4	0	0
14	10.2	2.0E-05	7.4E-02	33	2.9	5.0E-04	5.3E-01
15	9.2	3.8E-05	1.3E-01	34	6.8	1.3E-04	3.1E-01
16	16	1.0E-05	5.8E-02	35	4.3	1.7E-04	2.7E-01
17	12.7	1.0E-05	4.6E-02	36	40	2.9E-04	4.2E+00
18	2.2	4.0E-05	3.2E-02	37	3.7	0	0
19	1.2	1.0E-05	4.4E-03	38	5.6	3.0E-04	6.1E-01
				<b>Total</b>	<b>533.4</b>		<b>1.87E+01</b>

### 3.8.5 Adjustment of recharge during calibration

The recharge and EVT rates were adjusted during model calibration so that the following conditions were satisfied:

- The total recharge to the entire model domain is about 20 GL/year, of which about 2–3 GL/year applies to the area outside the basin margin.
- The model watertable matches the conceptual steady state watertable (see section 4.2.1).
- There is no significant water ponding above ground surface (ie no broad flooded areas).

- Distribution of recharge between Cardiff Sub-basin and the Premier Sub-basin is generally proportional to the surface areas of the sub-basins.

### 3.9 Representation of faults

Collie Basin has a large number of faults, the majority of which exhibit a northwesterly trend, along the long axis of the basin. Representing all the faults in the groundwater model would result in a very complex groundwater model. In addition, many of the faults are inferred and the locations are not known accurately. Accordingly, only those faults regarded as being major, or known to have an impact on groundwater flow within the basin, have been incorporated:

- **McAlinden Fault:** This fault forms the downgradient limit to mining for the Western 6 underground mine, and therefore represents a limit to the development of the underground mine void;
- **Eastern Fault:** Evidence exists that significant aquifer depressurisation at Muja Open Cut has had limited effect on bores in the Chicken Creek area, suggesting that faulting in the area is acting as a barrier to groundwater flow. Mine scale models constructed in the area have also assumed that the Eastern Fault acts as a low permeability barrier limiting groundwater flow (Dames & Moore, 1998);
- **Powerhouse Fault:** The Powerhouse Fault was chosen because it is extensive, and has the largest throw (up to 200 m) of the faults present in the area. As the fault lies between the Premier and Cardiff Sub-basins it also enables any modification to groundwater flow in the area, as it is inferred that a significant fault effect exists in this area.

Other faults in Cardiff Sub-basin area that have been included in the model are the Pendleton Fault, Scottish Fault, Grill Fault, Minningup Fault and the Cardiff Fault, all of which appear to influence groundwater flow in this area. The location of these faults is shown in Figure 11. The faults that displace the strata are predominantly normal faults with a NW strike, and having dips of 60-90°. For the model, it is assumed that all faults are vertical, allowing easier representation of the fault between layers. The faults are modeled using the Horizontal Flow Barrier (HFB) feature of MODFLOW. The Horizontal Flow Barrier module simulates thin, vertical low-permeability geologic features (eg faults) that impede the horizontal flow of groundwater. These geologic features are approximated as a series of horizontal flow barriers conceptually situated on the boundaries between pairs of adjacent cells. The sole function of the barrier is to lower the horizontal branch conductance between the two cells that it separates (Hsieh & Freckleton, 1993).

Where used in the model, faults are simulated from Layer 2 downwards. Layer 1 (Nakina Formation and surficial units) is not included as deposition of this unit post-dates faulting.

In GMS, the hydraulic effect of a fault is simulated by specifying a hydraulic characteristic that is equivalent to the transmissivity of the fault divided by its thickness (Brigham Young University, 2001). The hydraulic characteristic value is usually adjusted

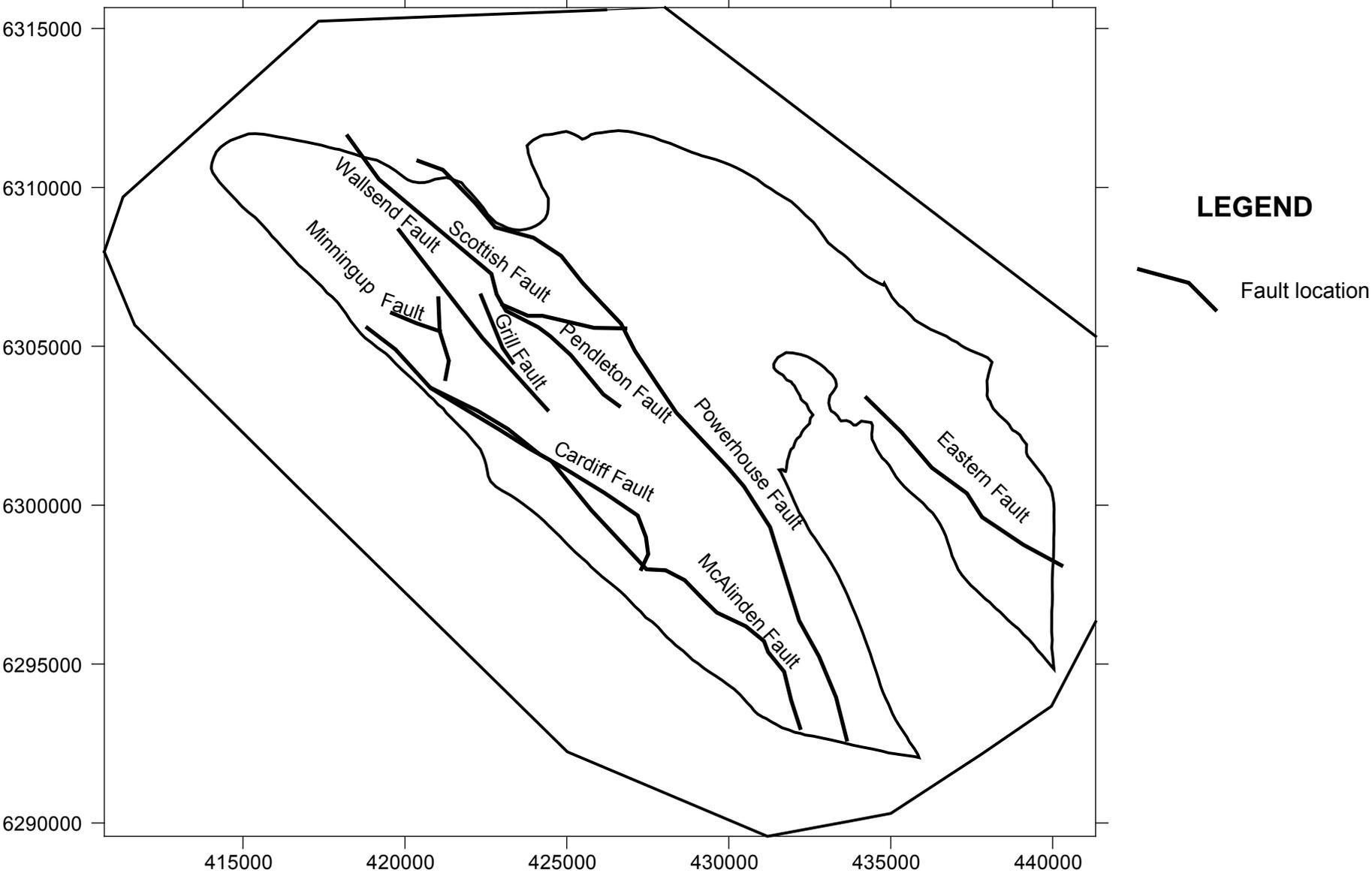


Figure 11. Location of faults

during model calibration to reflect the effect of the fault. In the current model, the hydraulic characteristic values for the McAlinden, Eastern and Powerhouse Faults are 180 m/d, 0.01 m/d and 0.01 m/d, respectively. Assuming that the faults have an average width of 1 m, the transmissivity of the McAlinden, Eastern and Powerhouse Faults is 180, 0.01 and 0.01 m<sup>2</sup>/day, respectively. This is to simulate that the Eastern and Powerhouse Faults act as flow barriers, as stated above, while the McAlinden Fault has been modeled as having a relatively large transmissivity. Other faults in the Cardiff Sub-basin have been assigned hydraulic characteristic of 9.5 m/d representing semi-transmissive faults.

It is generally considered that the faults have significant but variable effect on groundwater flow, and can act as either horizontal flow barriers or as vertical conduits that allow enhanced flow across aquitards. As such, it is considered that the HFB package alone may not adequately represent the impact of faults. This feature requires the hydraulic characteristic (hydraulic conductivity × thickness across the fault) to be input, allowing simulation of a fault with differing horizontal hydraulic conductivities in each layer. However, the package does not allow for vertical groundwater movement along faults – a feature that has been identified as significant in numerous investigations. This issue could have been resolved by applying fault hydraulic properties to individual cells along the strike of the fault. This would require small cell size along the strike of a fault, which would allow vertical movement along the fault if high vertical hydraulic conductivity were input to the cell. However, at this stage such application is not considered critical on a regional scale, and may be applied later to enhance local scale accuracy of the model.

## 3.10 Representation of mines

### 3.10.1 Open cut mines

The model layers, in the areas where the voids exist, were assigned a very high horizontal hydraulic conductivity (100 m/d) and a specific yield of 0.1 during the periods of dewatering. During the post-mining period (period of recovery) both horizontal and vertical hydraulic conductivities were made high (100 m/d) and the specific yield of 1.0 was used to allow the voids to be represented as water-filled bodies. Further details on representation of voids during periods of recovery are given later in section 5 under Predictive Simulations.

### 3.10.2 Underground mines

A number of dewatering well cells become dry during model calibration, particularly in the areas of the Western 2, Western 6 and Western 7 underground mines. When the well cell becomes dry, it becomes inactive, and further pumping from the cell does not take place. To avoid this, the horizontal hydraulic conductivity of dry well cells was increased to 2 m/d. In addition, the hydraulic conductivity of the entire Muja 3 (Model Layer 4) was given a relatively higher hydraulic conductivity of 1 m/d to represent the average hydraulic condition taking into account the widespread distribution of underground mines in this layer.

## 3.11 Surface water features

### 3.11.1 Rivers

Modelling of the interaction between the river and the groundwater system particularly at the pools is critical to the success of the model. Conceptually, it was considered that a pristine groundwater system would discharge, for at least part of the year, to the pools of the Collie River South Branch. During periods of high rainfall, the Collie River South Branch is a continuous river. When conditions are drier, flow in the river ceases and the river is discontinuous, and the pools exist as individual 'lakes' that leak water into the underlying aquifer. At some point, through a combination of evaporation and leakage, the pools dry up. The model has been constructed to represent this condition, as well as the condition of watertable recovery and subsequent discharge of the groundwater to pools.

The Collie River, East Branch and the South Branch are simulated by the River Package in the model. The riverbed conductance for most part of rivers is unknown. The conductance for the South Branch river pools, however, has been estimated by performing simple water balance analyses for the individual pools (Varma, 2002). The conductance value provided in Varma (2002) has dimensions  $[L]^2/[T]/[L]^2$ , ie conductance per unit area of the pool bed. As GMS requires the conductance per unit river length, the conductance values were multiplied by the width of river pools. This pool width was defined as the wet width depending on the depth of water in the pool. Therefore it may vary from the maximum pool width when the pool is full of water to a minimum when the pool is almost dry. An equivalent pool width was calculated by normalising the shape of the pool to be rectangular with its total volume unchanged. Table 6 lists the conductance values of the pools from Varma (2002) and the values used in the model.

Table 6. Riverbed conductance

Pool	Maximum width (m)	Normalised width (m)	Conductance per unit area (Varma, 2002) ( $m^2/d/m^2$ )	Conductance per unit length ( $m^2/d/m$ )
1	40.5	15.89	0.013	0.21
2	30.0	16.12	0.069	1.11
3	17.2	6.76	0.062	0.42
4	37.0	20.35	0.028	0.57
5	35.0	22.08	0.006	0.13
6	30.0	11.78	0.033	0.39
<b>Other river segments</b>				1.0–3.0

The bed of other river segments is shallow (containing minor river sediments) and hence the vertical hydraulic conductivity of the riverbed is likely to be close to that of

the Nakina Formation. Based on this, conductance values in the range of 1 to 3 m<sup>2</sup>/d/m were used, which is equivalent to the product of the vertical hydraulic conductivity of the Nakina Formation (0.1 m/d) with an approximate river width of 10 m to 40 m with most parts of the river having a conductance of 2 m<sup>2</sup>/d/m.

Due to the lack of relevant observation data, the hydraulic conductance of riverbed sediments in the model for most parts of the Collie River and its branches cannot be supported or calibrated. In addition, the shape of the river is not well known. Data from a longitudinal survey along the centreline of the Collie River South Branch was available at pools but cross-sectional profiles were not available. These would have been valuable in providing information on the profile and capacity of each of the pools accurately. In addition, little data exists for the riverbed elevation and profile along the Collie River East Branch. Available data consists of surveys only in the vicinity of existing stream gauging stations. Additional river data should be obtained in order to improve the model performance.

The river and pool stages during the transient calibration were constant, equivalent to the median annual pool and river stage. However, for running prediction simulations for assessing water levels changes adjacent to the river pools, it was considered appropriate to vary the pool stage with time thus simulating the condition whereby the water levels adjacent to the pools rise and maintain progressively higher water levels in the pools with time. The methodology is explained in section 5 under Prediction Simulations.

A literature review was undertaken to compare the packages available for MODFLOW to represent detailed interactions between the surface water and groundwater system. A methodology was then developed to allow modelling of surface water – groundwater interactions at the pools by extending the capability of the simple but stable River Package of MODFLOW. This method allows the river stage (in pools) to be time-dependent and updated for each time step based on the surface water balance calculation for the river cells. The drying and re-wetting processes of the river cells can be simulated with minimal additional effort. An assessment of the different packages available for carrying out surface water and groundwater interaction, including details of the selected methodology with examples, are presented in Appendix A.

### 3.11.2 Creeks and wetlands

Creeks in the basin (Figure 5) are simulated as groundwater discharge areas using the Drain Package in MODFLOW. When the watertable is higher than the drain elevation, groundwater discharges into the drain. The groundwater discharge is proportional to the head difference between the groundwater and drain elevation, and the drain sediment conductance. If the watertable is lower than the drain elevation, the drain will not have any effect on the flow. The drain elevation is set to the topographic elevation of the creeks and wetland areas. A relatively large conductance value was assigned to drain cells (5 to 10 m<sup>2</sup>/day/m) to ensure that the watertable is not significantly higher than the ground surface in the creeks. This is based on the assumption that no ponding occurs in creeks.

For some wetlands such as the swamp areas, a net groundwater discharge may occur through evapotranspiration (ET). In this case, using the Recharge Package and assigning a zero recharge value alone does not simulate the water actually leaving the system. It is therefore regarded as appropriate to include an ET condition using the ET Package in MODFLOW. The ET Package requires the input of the potential maximum ET rate and an extinction depth. The actual ET rate that applies to a model cell is a linear function of the watertable depth below ground surface. A maximum ET rate of 0.0003 m/d with an extinction depth of 3 m is used in the model, ie the actual ET rate is zero for the areas with a watertable depth equal to or greater than 3 m.

## 3.12 Wells

### 3.12.1 Issues with bore construction

GMS requires bore ID, easting, northing, collar RL, depth to screen, and length of screen for input to the model. From this information GMS locates the bore spatially, and assigns a pumping depth. If the screened depth and length places the screened interval across a number of model layers, the pumping rate from the bore is divided between layers based on the percentage of screen length in each layer and the transmissivity of the intercepted layer. If the screened length and depth to screen of a bore is not known, then the layers from which abstraction occurs are assigned manually.

### 3.12.2 Wellfields

#### 3.12.2.1 Shotts wellfield

The six bores in the Shotts wellfield were drilled between September 1979 (Shotts 6A) and April 1980 (Shotts 3). Annual abstraction data was available from 1984 onwards and monthly groundwater abstraction data was available from November 1985 onwards. To fill the gap between January 1984 and November 1985, the annual production data was divided evenly among the six bores on a monthly basis.

#### 3.12.2.2 Cardiff South wellfield

Data-loggers measure flow at collection lines for Cardiff bores 1&3, 2&4, and 5&6. However the individual bores are judged to be too far apart to lump the flows together, so metered flow has been distributed to the bores based on the design capacity of each bore. For example, Cardiff 2 has a design capacity of 3500 kL/d, and Cardiff 4 has a design capacity of 2000 kL/d. Therefore 64% of the metered flow is assigned to Cardiff 2, and 36% of the metered flow is assigned to Cardiff 4.

#### 3.12.2.3 Abstraction from mines

Records of groundwater abstraction were obtained from a number of sources for wellfields associated with dewatering of coal mines (Western 2, Western 6, Western 7, WO5, WO5H, Ewington II, Premier, Muja, and Chicken Creek) in the basin. As the abstraction data were obtained from a number of sources, often obtained as paper

records, it was uncertain that all abstraction data were obtained. Where data were obtained from a number of sources, checks were undertaken to determine whether the volumes matched. If the volumes matched for periods where data were derived from a number of sources, a higher degree of confidence was placed in the records that extended for longer periods.

### 3.12.3 Groundwater abstraction prior to 1984

Mine dewatering in the basin has occurred since 1898, however there are no records of pumping available for the period before 1984. Varma (2002) has estimated pumping by correlating to the tonnage of coal mined in different areas of the basin giving a 2-year time lag between dewatering and coal production (Figures 12 and 13). Pumping locations and rates were adjusted to generate hydraulic heads close to that actually observed at a number of locations in 1984.

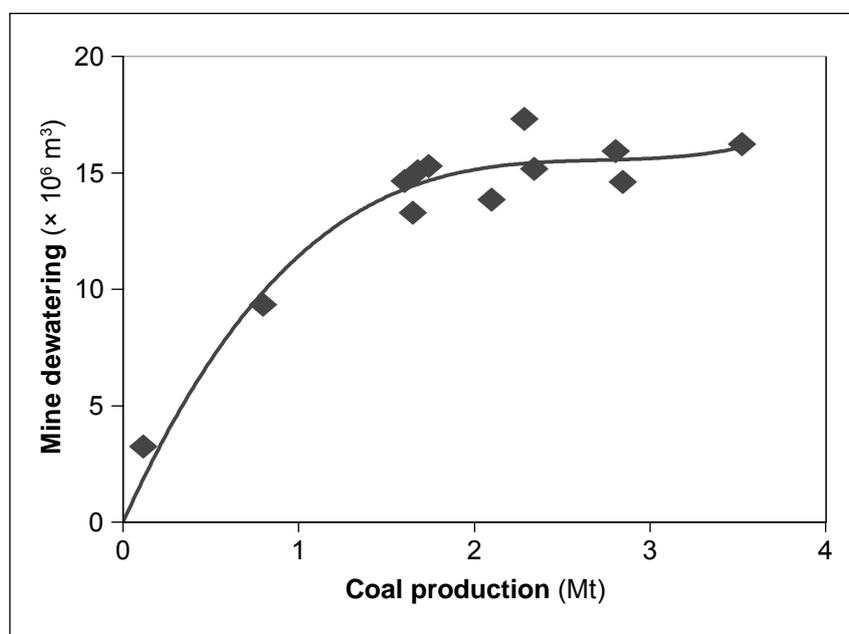


Figure 12. Coal production and mine dewatering (Cardiff Sub-basin)

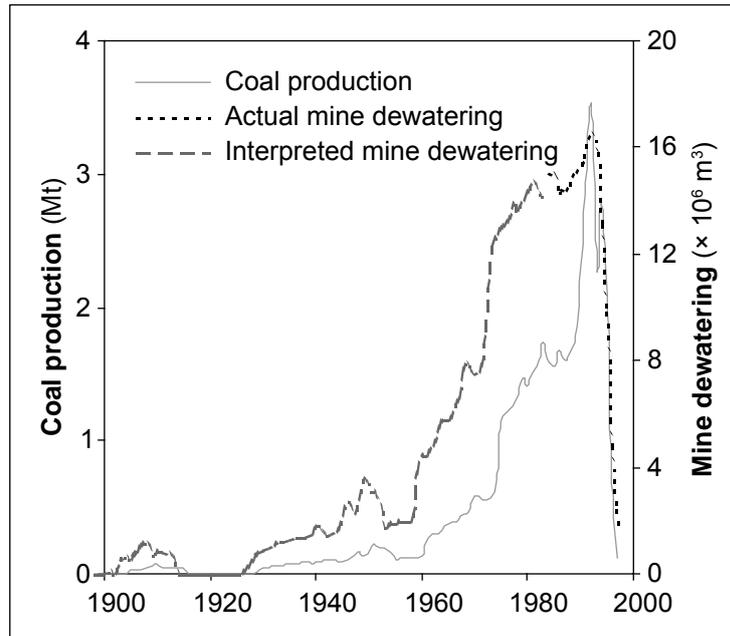


Figure 13. Interpreted historical dewatering

### 3.13 Model test runs

A number of model runs were performed after the model was initially constructed to test the numerical stability of the model. River cells and drain cells were checked to ensure that they were operative. Grid configuration was also checked to ensure that the model domain was properly discretised, and that no cells existed having cell volume zero and cases of the bottom elevation of a cell being higher than its top elevation were not present. Different equation solvers were also attempted and they provided the same solution (which is expected if a numerical model is properly set up). These model test runs confirmed that the model is numerically stable and the physical conditions have been correctly represented in the model, which provided confidence in progressing to the model calibrations.

## 4 Model calibration

### 4.1 Calibration strategy

The model has been calibrated under both steady state and transient conditions. The model calibration strategy involved comparison of model-generated information with observed (or interpreted) values. The following aspects were considered while assessing the calibration of the model:

- Watertable at steady state (conceptual pre-mining) condition;
- Water balance components in steady state condition;
- Comparison of hydrographs in transient condition;
- Water balance in transient conditions;
- Watertable configuration in transient condition; and
- Water level drawdowns in areas of large abstractions.

The steady state calibration was undertaken prior to a transient calibration as a test of the components of the water balance. Groundwater recharge and discharge areas were also correlated with the groundwater flow directions. Parameters such as rainfall recharge rate, riverbed and drain conductance were calibrated in the steady state condition. Hydraulic conductivity was also adjusted during the steady state calibration. The head solution generated from the steady state model was then utilised as a starting head for running of the model in the subsequent transient calibration stage. The transient calibration was performed to adjust storage coefficients, and to test the response of the model to dynamic stresses (eg changes in pumping). This was implemented by trying to match model-generated heads with observed hydrographs. Where multiple aquifers were monitored in the one model layer, it was assumed that the hydrograph from the shallowest part of the aquifer represented the potentiometric head for that layer and was then used as a calibration target for that particular model layer.

### 4.2 Steady state calibration

#### 4.2.1 Pre-stress steady state watertable

It was assumed that the groundwater levels prior to any mining activity in the Collie Basin were under natural equilibrium and hence in a 'steady state' condition. A conceptual watertable representing that condition was first generated and served as one of the calibration performance measures for the steady state calibration. This conceptual watertable was generated, based on an understanding of the groundwater sources and sinks, where the major source of recharge to the groundwater system was from rainfall and the major groundwater discharge areas were the Collie River and its tributaries. In this condition, it is assumed that the watertable is closest to the ground

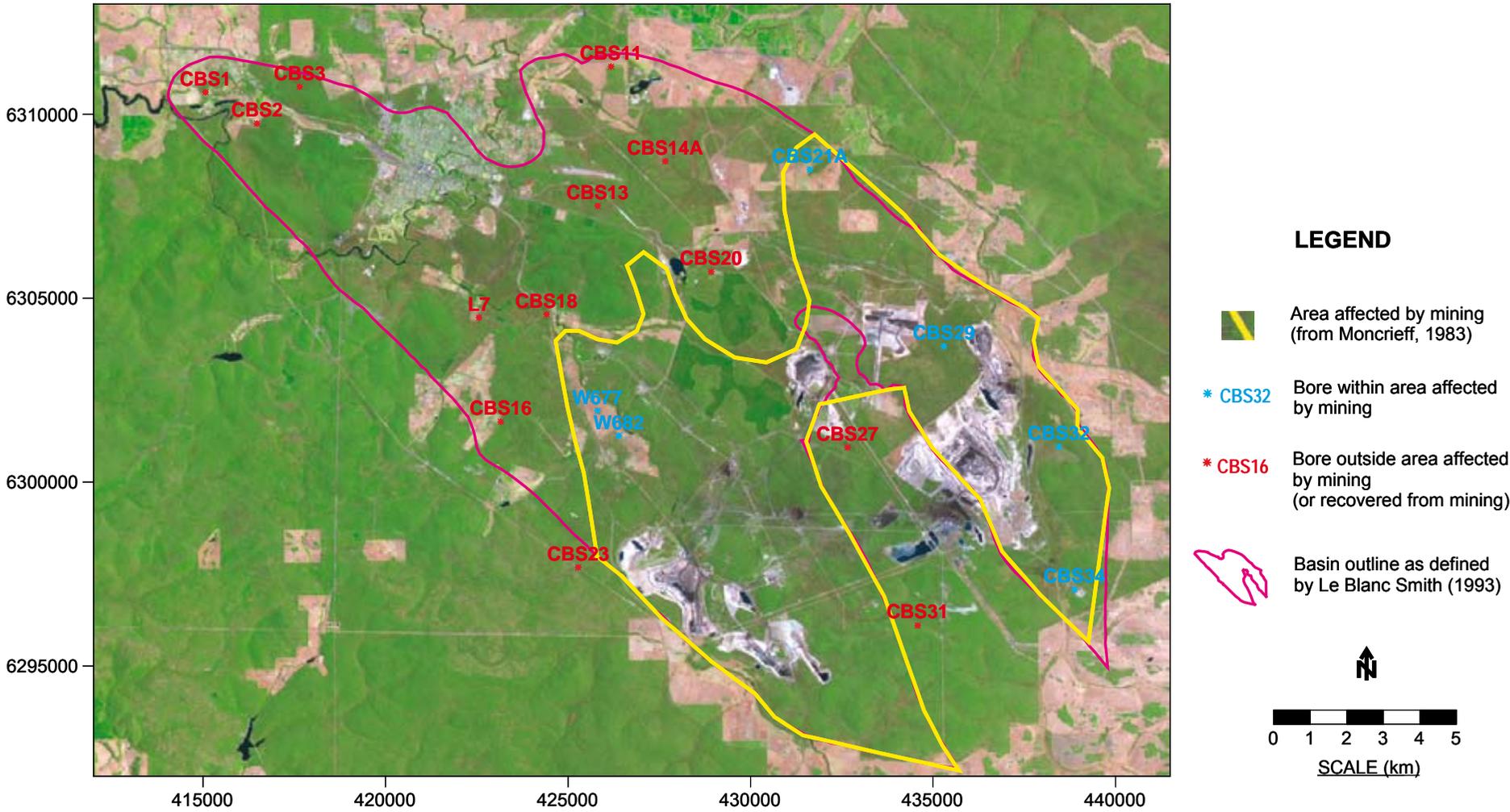


Figure 14. Area of the Colliie Basin affected by abstraction

surface near rivers/creeks and wetlands, and deepest at the hills and highlands. Heads from observation bores in areas unaffected by recent mining activities were used as calibration points. Figure 15 that has been derived from Moncrieff (1993) shows the area of the basin interpreted as being unaffected by mining. The hydrographs of a number of watertable bores were analysed to determine whether they had steady trends over the period monitored (Fig. 15).

If the head at a bore did not show a noticeable head decline or increase, then the average water level was used as a data point in the preparation of the watertable map. Other data points for the steady state watertable map were generated from:

- The known reduced level (RL) of the stream bed at a number of stream gauging stations;
- Dummy points generated along rivers/creeks where an assumption was made that the watertable was close to the land surface. The RLs were taken from 1:25 000 scale topographic sheets;
- Dummy points taken along bedrock ridges, which were used to obtain a 'shape' of the watertable that fitted the conceptual configuration. The RLs were taken from 1:25 000 scale topographic sheets;
- Dummy points entered along the Stockton Ridge exposure, where prior studies (eg Moncrieff, 1993) have suggested that the RL of the original watertable was around 230 m AHD.

Using the data points described above, a pre-mining steady state watertable was inferred as plotted in Figure 16. In the areas where insufficient water level observation data was available or 'dummy' points were taken, the head contours should only be regarded as representing the general flow directions and not the true watertable elevation. In such areas the mathematically interpreted steady state watertable can only be compared qualitatively with the model-generated watertable in most for a comparison of general flow direction and not the actual watertable elevation. Quantitative comparisons between observed and calculated water levels can be made only at the points where real observation data is available.

## 4.2.2 Calibration measures

### 4.2.2.1 General

Due to the relative lack of water level data at depth, a key measure of model performance has been taken as the comparison of magnitude of various water balance components in the model with those reported in literature (CWAG, 1996). Other quantitative aspects, such as the relationship between modeled and measured heads, have been assessed. In addition, qualitative calibration, such as assessment of modeled water level contours in areas of large-scale groundwater abstraction were undertaken.

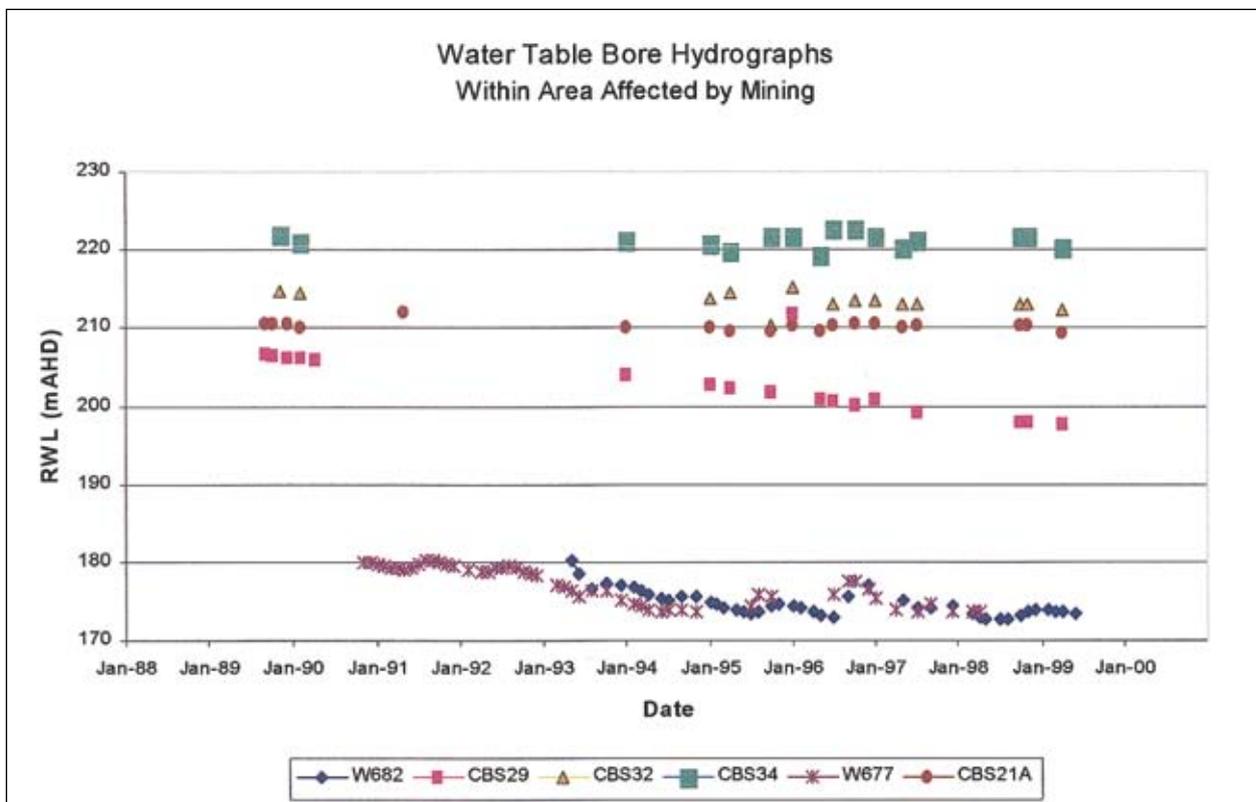
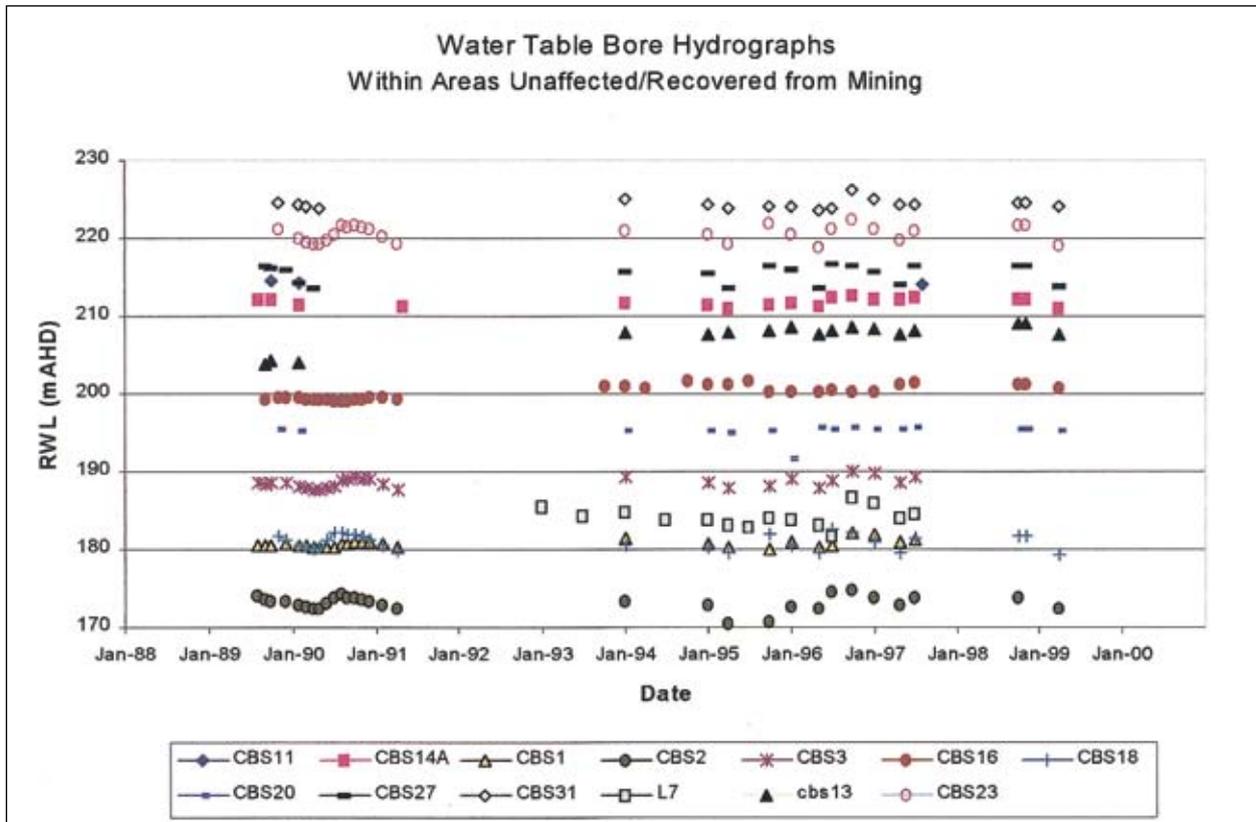


Figure 15. Sample hydrographs

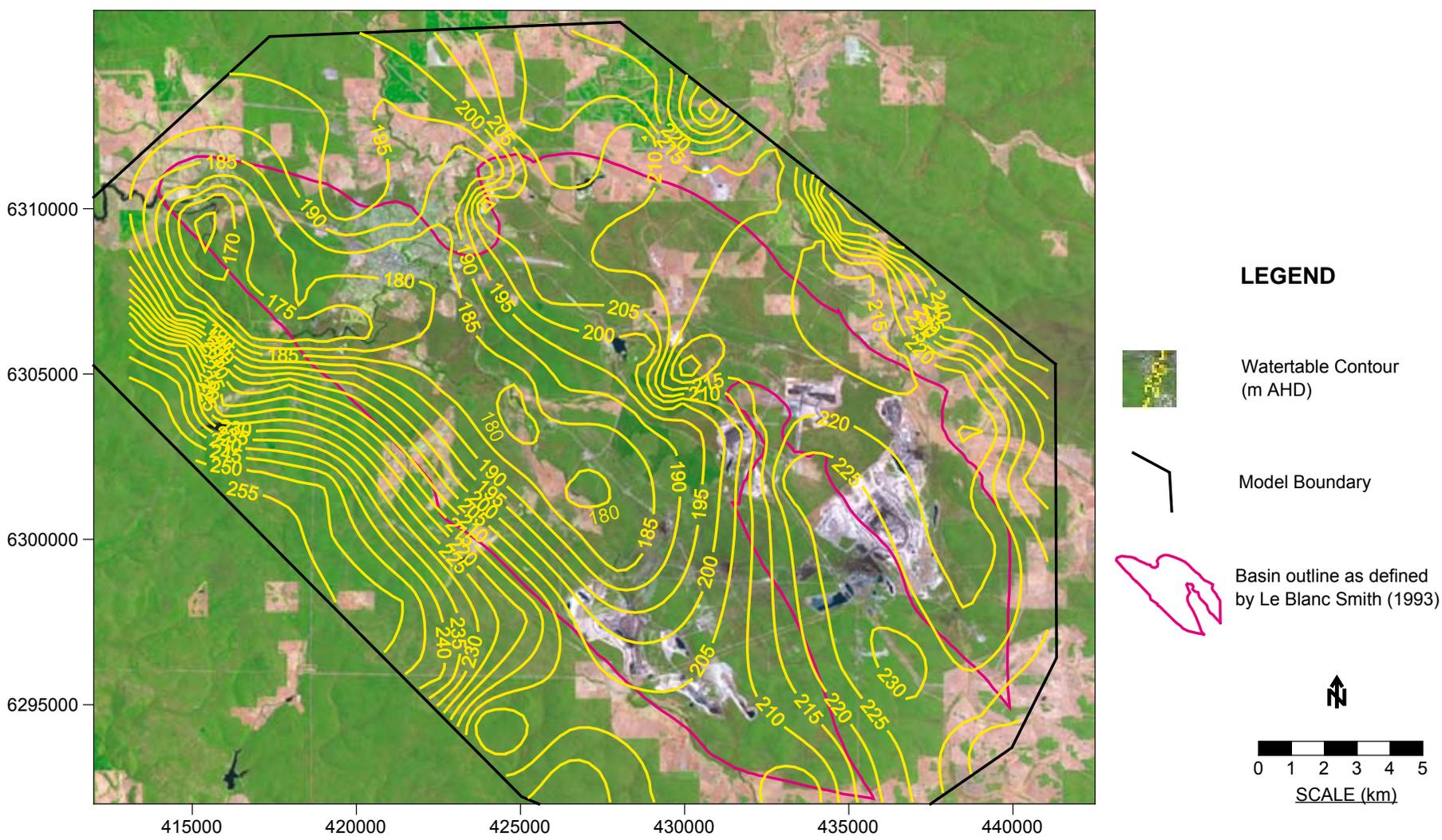


Figure 16. Conceptual pre-mining watertable

#### 4.2.2.2 Water balance analysis

The water balance for the entire model domain is presented in Table 7.

Table 7. Volumetric budget for entire model domain - steady state model

Source	IN (GL/Year)	Percentage of total	OUT (GL/Year)	Percentage of total
Rainfall recharge	18.7	97.3	-	-
Rivers and creeks	0.5	2.7	16.2	84.3
Wetlands (via ET)	-	-	3.0	15.7
<b>Total</b>	<b>19.2</b>	<b>100</b>	<b>19.2</b>	<b>100</b>

The water budget is consistent with the conceptual model in that the major source of groundwater is rainfall recharge (97.3%) and that groundwater discharges mainly through baseflow to rivers (84.3%) and by evaporation at wetlands (15.7%). Comparatively little recharge occurs via river leakage (0.5 GL/year). The small percentage leaking from the river is to be expected for this simulation, as the majority of water leaving the model is through groundwater discharge to rivers or drains as defined in the conceptual model. The water balance components for individual aquifers are provided in a flowchart in Appendix B. The water balances of individual model layers show that minor leakage occurs between layers, whereas most water is received as recharge through Nakina Formation in the areas of the Permian subcrop. The flow magnitudes in the layers are therefore generally proportional to the subcrop areas beneath the Nakina Formation. The magnitude of flow in each layer will have a relationship to the horizontal/vertical conductivity for each layer. For example, there is a relatively high volume of water moving through the Allanson Sandstone, which is because the Kh in the Allanson Sandstone is significantly higher than for other layers, and the layer is thicker. Therefore, the transmissivity in this layer is high compared to other layers and this causes greater flow.

#### 4.2.2.3 Observed versus simulated heads

Comparison of simulated with observed heads was made for 35 watertable bores as shown in Figure 17.

The calibration statistics shows that the mean error is 0.35 m, the mean absolute error (where all errors are converted to positive values so that positives and negatives do not cancel each other out) is 1.64 m, and the root mean square error is 2.14 m. The simulated pre-stress watertable is included in Appendix D as Figure D-1 for comparison with the conceptual pre-stress watertable presented in Figure 16.

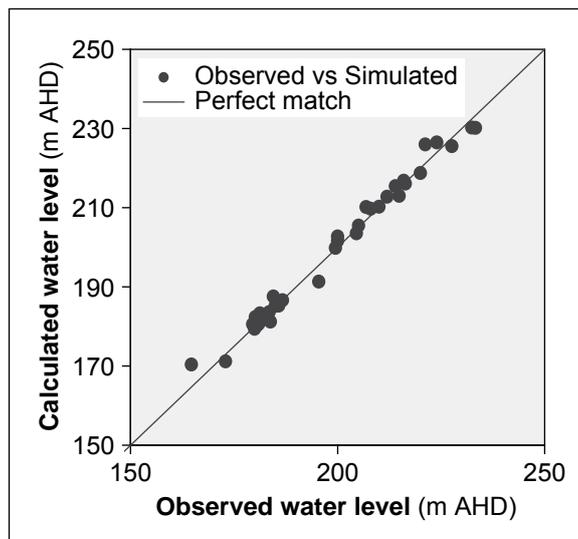


Figure 17. Observed vs simulated heads in steady state calibration

#### 4.2.2.4 Flow patterns

Flow patterns in two vertical cross-sections are shown in Figure 18. The flow arrows only represent flow direction, and the magnitude of flow velocity is not indicated due to the limitations of flow velocity interpretation in GMS. As the vertical scale of the section is magnified, the flow arrows have been exaggerated in the vertical direction. Figure 18 (a) shows that groundwater flows from the Premier Sub-basin to the Cardiff Sub-basin in the northern Collie Basin. Groundwater mainly discharges at the Collie River and its South and East Branches. Figure 18 (b) shows that the general flow direction is from the southeast to the northwest where groundwater exits at the Collie River South Branch. These flow patterns are consistent with the conceptual groundwater flow as shown in Moncrieff (1993, Figure 5).

In addition, flow details in the upper section of each figure are presented in Figures 19 and 20. These figures were generated by digitising model output to allow presentation on a larger scale. Figure 19 shows that water exchange occurs between the Nakina Formation and the underlying units through the subcrop zones as well as via vertical leakage between units. Figure 20 shows that the flow direction in the deep aquifers, eg Premier Coal Measures is mainly horizontal. In shallow layers (eg Muja 1, Muja 2 and Muja 3), as groundwater discharges to the river in the overlying Nakina Formation a vertical flow component towards the Nakina Formation is prominent.

#### 4.2.3 Summary

The simulation results presented in this section include the overall water balance for the entire model domain, water balance components for individual layers and flow patterns for typical vertical cross-sections. These results are consistent with those reported in literature, supporting the view that in general the Collie Basin water balance, groundwater discharge areas and groundwater flow direction have been adequately simulated in the model. The calibrated parameters were used as a starting case for the next step in the calibration process, ie the transient calibration.

## 4.3 Transient calibration

### 4.3.1 General

The transient calibration enables consideration of aquifer storage changes and the effects of dynamic stresses (eg changes in pumping over time) on the modeled groundwater system of the Collie Basin. The transient calibration was also used to refine the calibration of other aquifer parameters such as the hydraulic conductivities. These adjusted parameters were re-input to the steady state model to test their effect on the water balance components and steady state water levels.

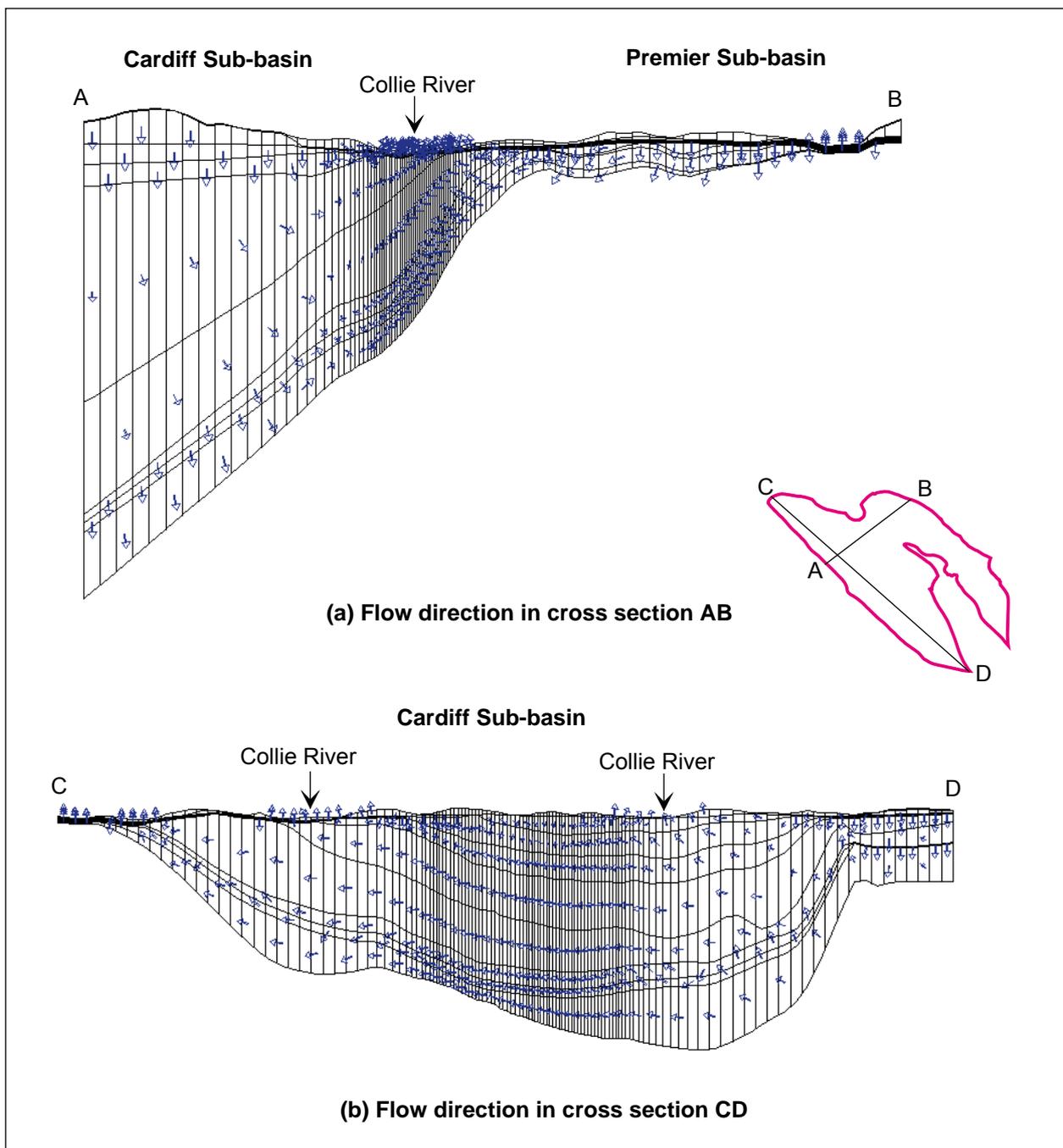


Figure 18. Flow patterns in vertical cross-section - steady state flow

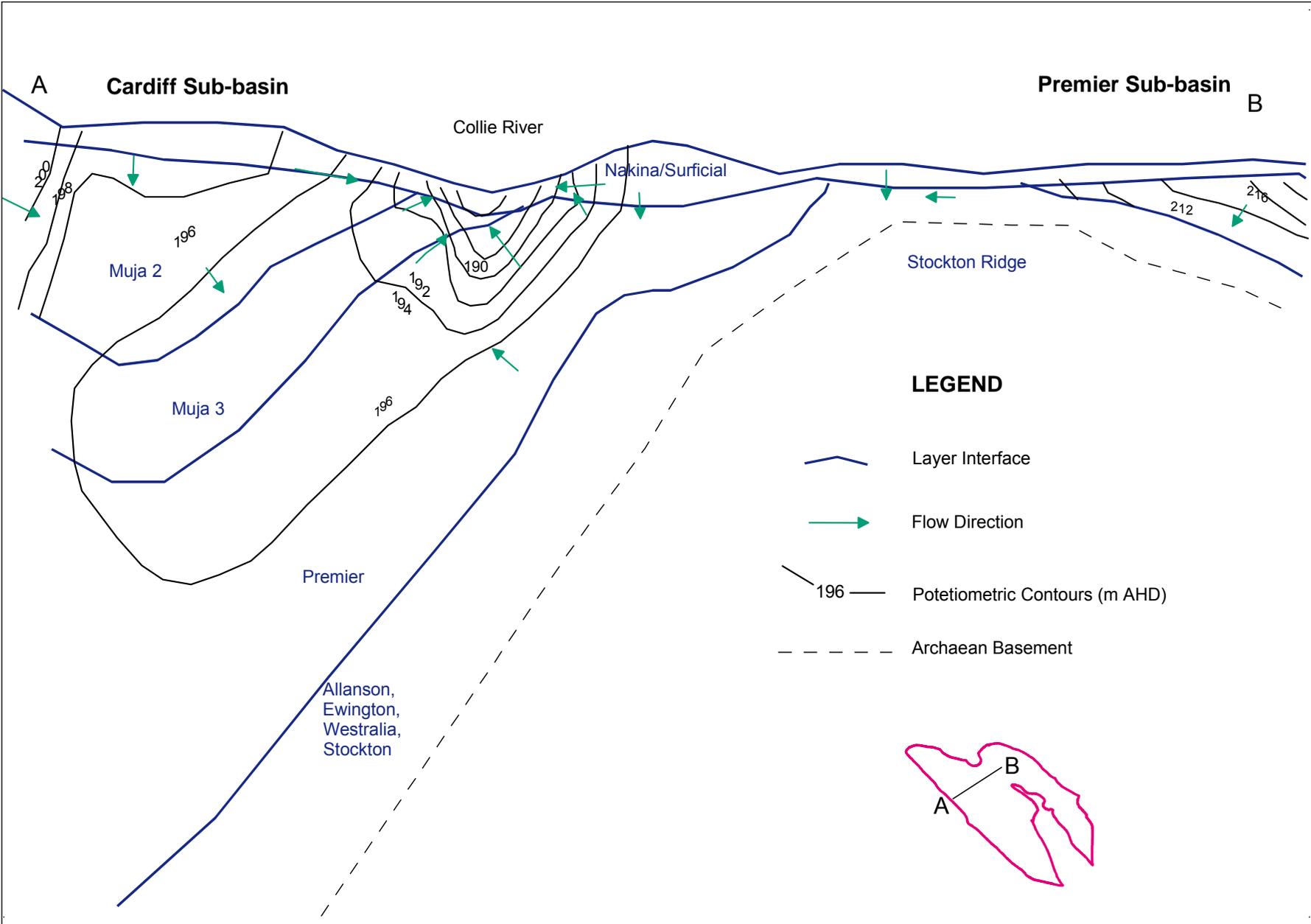


Figure 19. Flow patterns in section (SW-NE)

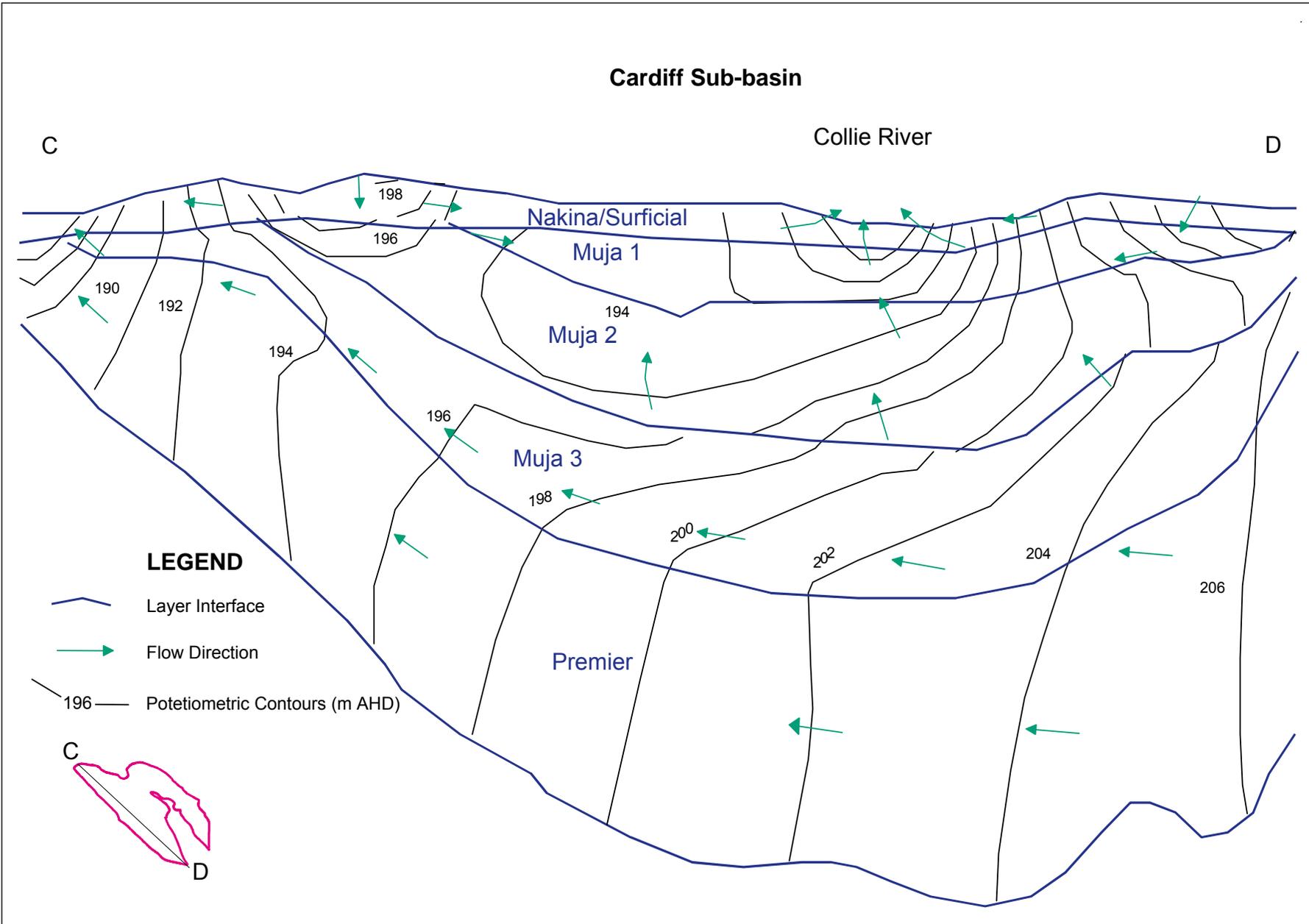


Figure 20. Flow patterns in section (NW-SE)

### 4.3.2 Calibration period and initial conditions

Coal mining and hence dewatering in Collie Basin commenced in 1898, however records of pumping are available only from 1984 onwards. Although the transient model covers the period from 1898 to 1999, calibration was focused on the more recent period, ie 1984 to 1999, for which the actual pumping and head observation data are available. Two transient models were developed; one for the period of 1898 to 1984 and the other from 1984 to 1999. The purpose of the transient model for the period of 1898 to 1984 was essentially to generate the initial heads for the 1984 to 1999 transient model. Initial heads for the 1898 to 1984 model were obtained from the steady state model. Calibration of the 1898 to 1984 model included ensuring that model-generated heads for 1984 compared well with known data at several boresites.

Varma (2002) established several correlations between coal mined in the basin and groundwater abstracted for mining, by utilising data from 1984 to 1999 for different parts of the basin. The correlations were applied to annual coal production from individual mines (source: Department of Resources Development) from 1898 to 1984 to obtain coarse estimates of annual groundwater abstractions. Examples of such interpretation for Muja Coal Measures in Cardiff Sub-basin are shown in Figures 12 and 13. Actual pumping data were used from 1984 to 1999. Assumptions and approximations were introduced in terms of the location and screen lengths for wells for which no data was available.

### 4.3.3 Discretisation of time

Time is discretised in MODFLOW into stress periods (between which model stresses can change) and time steps (a number of time steps make up each stress period; calculations are made during each time step, but model stresses do not change for the time steps). For the period of 1898 to 1984, yearly stress periods (86 in total) having a monthly time step were applied in view of the pumping rate being estimated on an annual basis. However, monthly stress periods were used for the transient model from 1984 to 1999, having 191 stress periods in total. Each stress period has 30.44 days and was subsequently discretised into five time steps. This time discretisation was tested to be sufficiently small to produce an accurate solution.

### 4.3.4 Synchronisation of models

Following the initial steady state modelling and the transient modelling, model parameters that were adjusted during the transient process were fed back into the steady state model. This process was then repeated (ie head distributions generated from the steady state model were used as starting heads for the transient model) until both models were calibrated.

### 4.3.5 Calibration measures

#### 4.3.5.1 *Calibrated parameters*

Transient calibration for selected hydraulic parameters was undertaken and the final parameters are presented in Table 8. The calibrated hydraulic parameters for some

layers are significantly different from those obtained by other methods (Table 3). There is a lack of data at depth in the Permian sediments. Around 80% of groundwater observation data are from the upper 100 m of the basin, with the deepest observation bore just over 300 m deep. Most of the derived parameters are representative of Permian strata at shallow depths and in areas of their subcrop beneath Nakina Formation. Hence, hydraulic conductivities derived previously are likely to be different from those calibrated in the model. During model calibration, the effects of a range of parameter values was also assessed. The horizontal conductivity for shallow aquifers was based on the values used in the calibrated steady state model, with further adjustment undertaken for layers for which data existed. The vertical hydraulic conductivity was adjusted in the transient model in the range of 2 to 3 orders in magnitude less than the estimated horizontal value (Geo-Eng, 2000).

Since the vertical hydraulic conductivity controls the vertical leakage between layers and is a sensitive parameter for head drawdown, the vertical hydraulic conductivity was adjusted so that the head decline trend was in general agreement with the observed hydrographs. The specific storage was then adjusted to refine the trend in heads. The specific yield is only applicable to unconfined aquifers and is not a sensitive parameter for the Muja 2, Muja 3, and the lower hydrostratigraphic layers, which are mostly confined. Therefore for these layers specific yield cannot be efficiently determined from the model and previously estimated values were used for final model input. Although great efforts were made in systematically adjusting the parameters during model calibration, further field evidence should be sought to provide justification and to increase the confidence in these values. The final calibrated hydraulic properties in the model are presented in Table 8.

#### 4.3.5.2 Observed versus simulated heads

Comparisons of modeled and observed hydrographs at a number of bore sites are shown in Figures 21-26. In Muja 3, good agreements are obtained at ACIRL9#2, ACIRL6#2 and W410#2 in Western 6 area. The computed head is higher than that observed at bores W645#K2F, W655#K2R, and D122 in the Western 7 area. It is noted that ACIRL9#2 and ACIRL6#2 monitor shallow aquifers in Muja 3, whilst W645#K2F, W655#K2R monitor the deep aquifers. There is a vertical downward hydraulic gradient in Muja 3, and therefore the hydraulic head monitored in the deep aquifers is lower than that in the shallow aquifer. The model-generated head is likely to represent the head in the shallow aquifers (eg good agreements at ACIRL bores in Western 6 area), and discrepancies are observed when comparing with the head in deep aquifers (eg W645, W655 and D122 bores). The significant vertical hydraulic gradient within Muja 3 cannot be simulated in the model unless multiple model layers are used to discretise Muja 3 or a local scale model is used. Some discrepancy is also possible because of the use of a constant recharge in the model. In 1996, in particular, the rainfall over the basin was about 25% higher than the long-term average.

In Muja 2, hydrographs are available for two observation bores, ACIRL6#5 and W410#5, for comparison. Satisfactory agreement is obtained at bore ACIRL6#5, while the model-generated head is higher than the observed at W410#5. This is because the observed head is lower at W410#5 than at ACIRL6#5 (eg 7 m lower in 1990). These two

bores, however, are very close (only 1 cell apart in the model), and the discrepancies in the observed heads at these two bores may be due to local geological features that are not represented in the model. It is also noted that the computed head fluctuates around 1985 and 1998 at bores ACIRL6#5 and W410#5. This fluctuation is in response to the variation in pumping in the vicinity. The observed head, however, does not show this response, as the bores were dry at that time probably due to increased pumping. Comparison of computed and observed hydrographs of bores at watertable within the Permian aquifers show good calibration in terms of trends (2523a, CBS17A, CBS18, CBS25, CBS29, CBS32, D198A, MER2A, MEW14A). However, actual values may differ in some cases.

Table 8. Collie Basin model - hydraulic parameters

Model Layer	Zone	Kx (m/day)	Kz (m/day)	Base elevation (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	6.0e-3	Only one zone	5e-4	0.1
3 Muja 2	I	0.5	2.0e-3 (5.0e-3 in PSB*)	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	1.0 (0.5 in PSB)	7.0e-4 (5.0e-3 in PSB)	175 to -50	1e-6	0.1
	II	0.1	7.0e-5	-50 to -200 (not present in PSB)	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	3.0e-3	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	2.0e-3	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

\*PSB = Premier Sub-basin

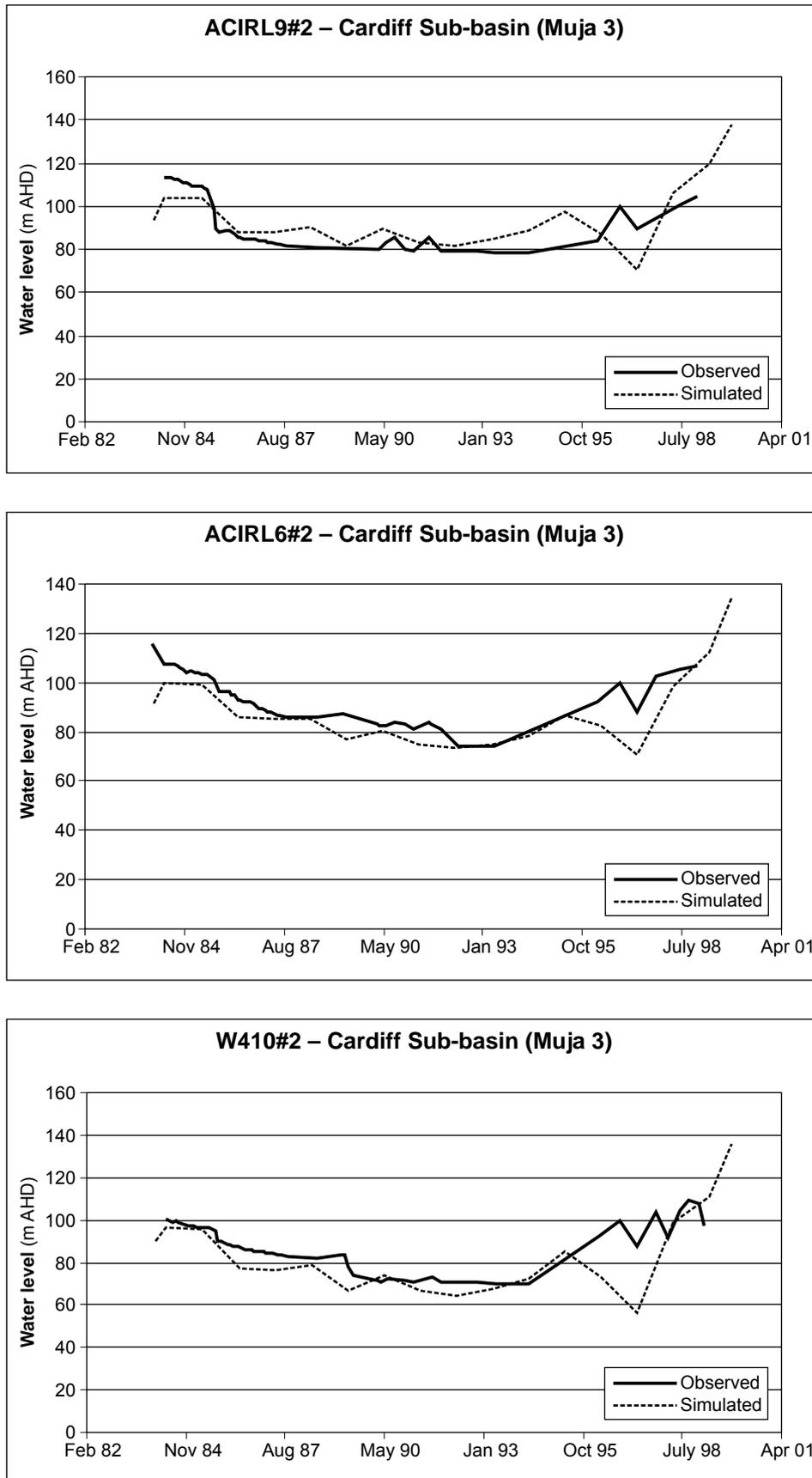


Figure 21. Calibration hydrographs (Set 1)

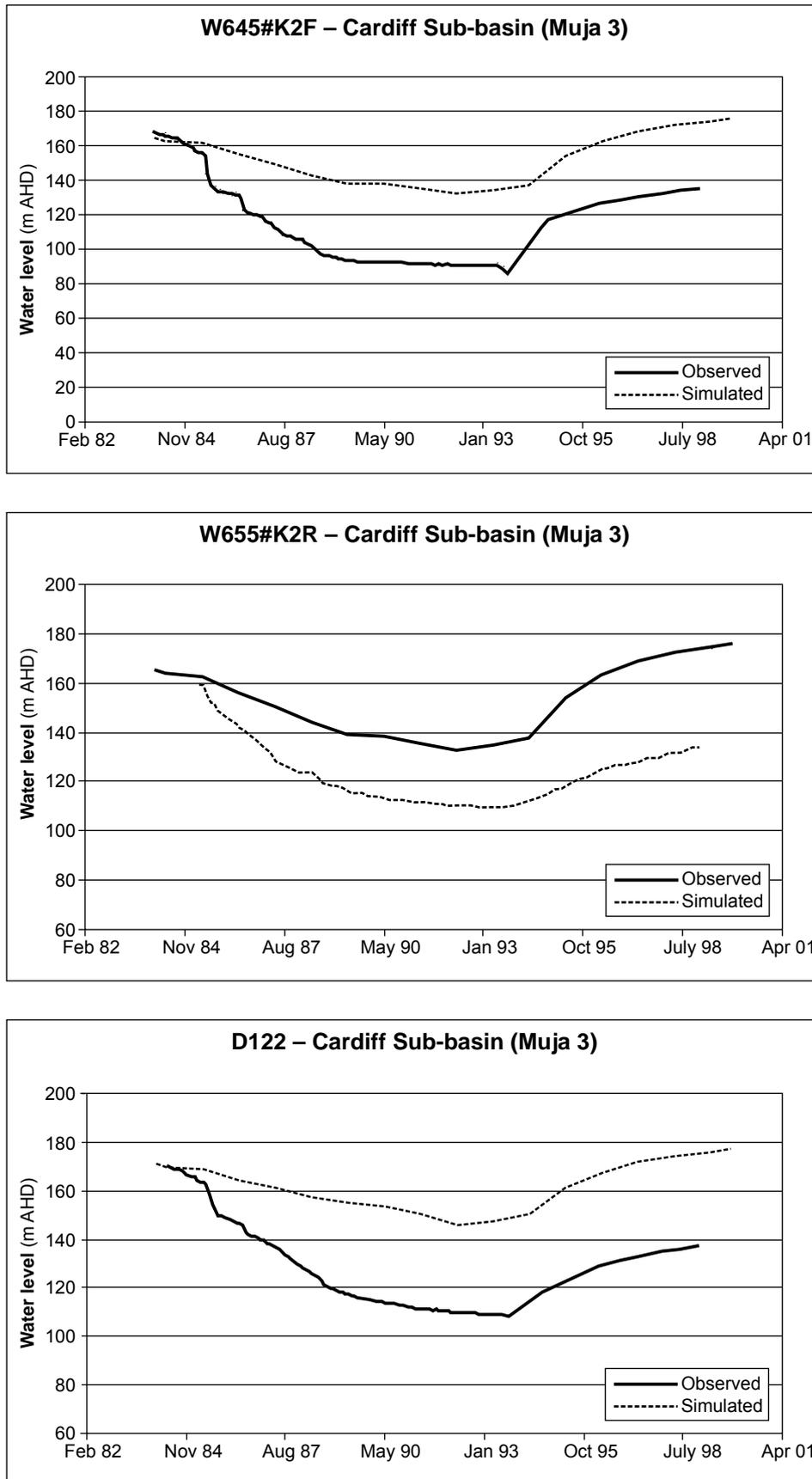


Figure 22. Calibration hydrographs (Set 2)

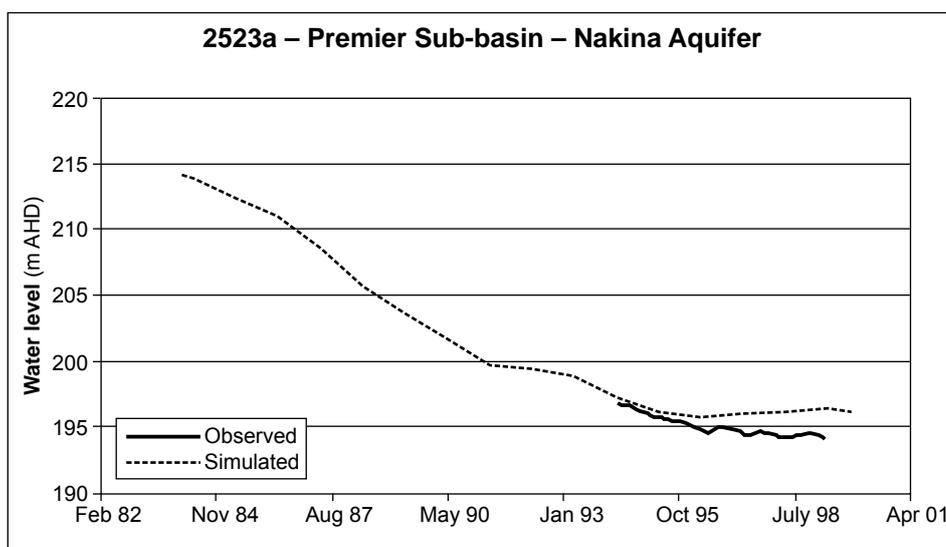
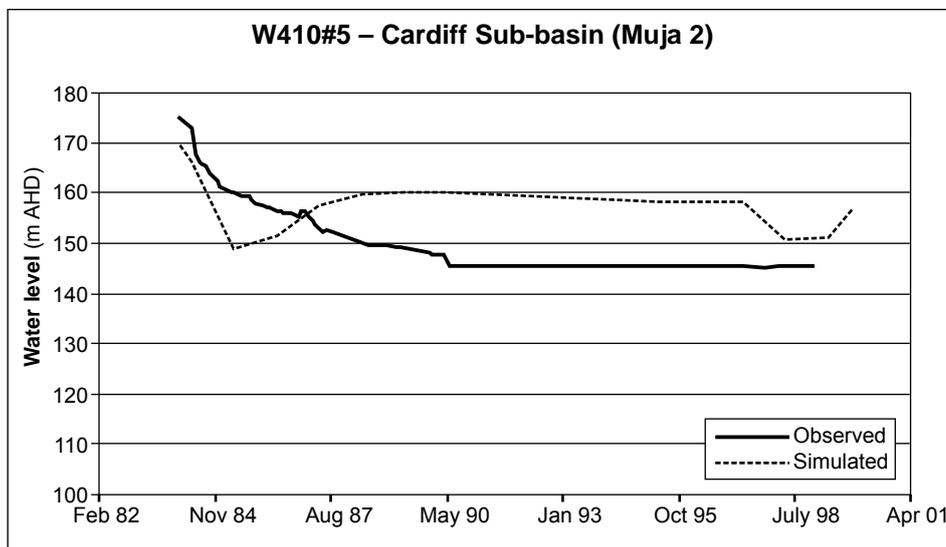
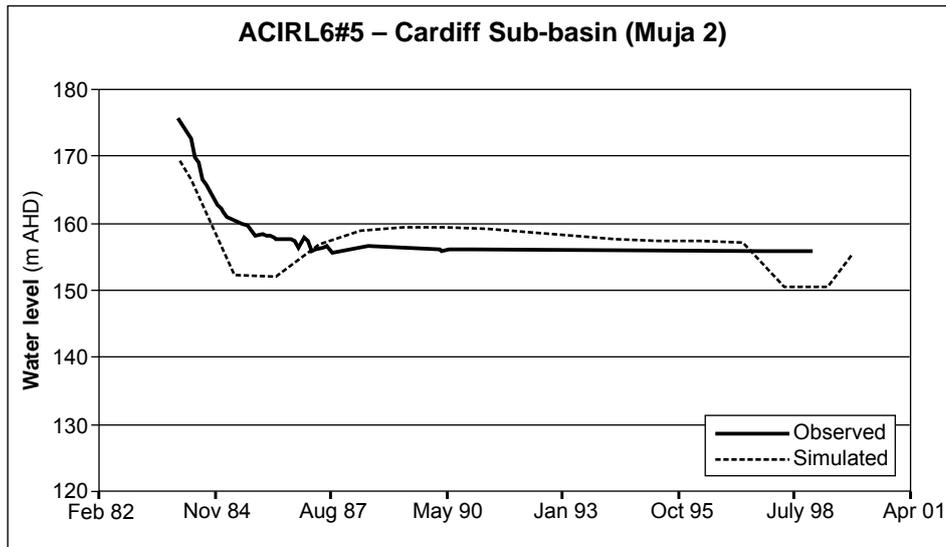


Figure 23. Calibration hydrographs (Set 3)

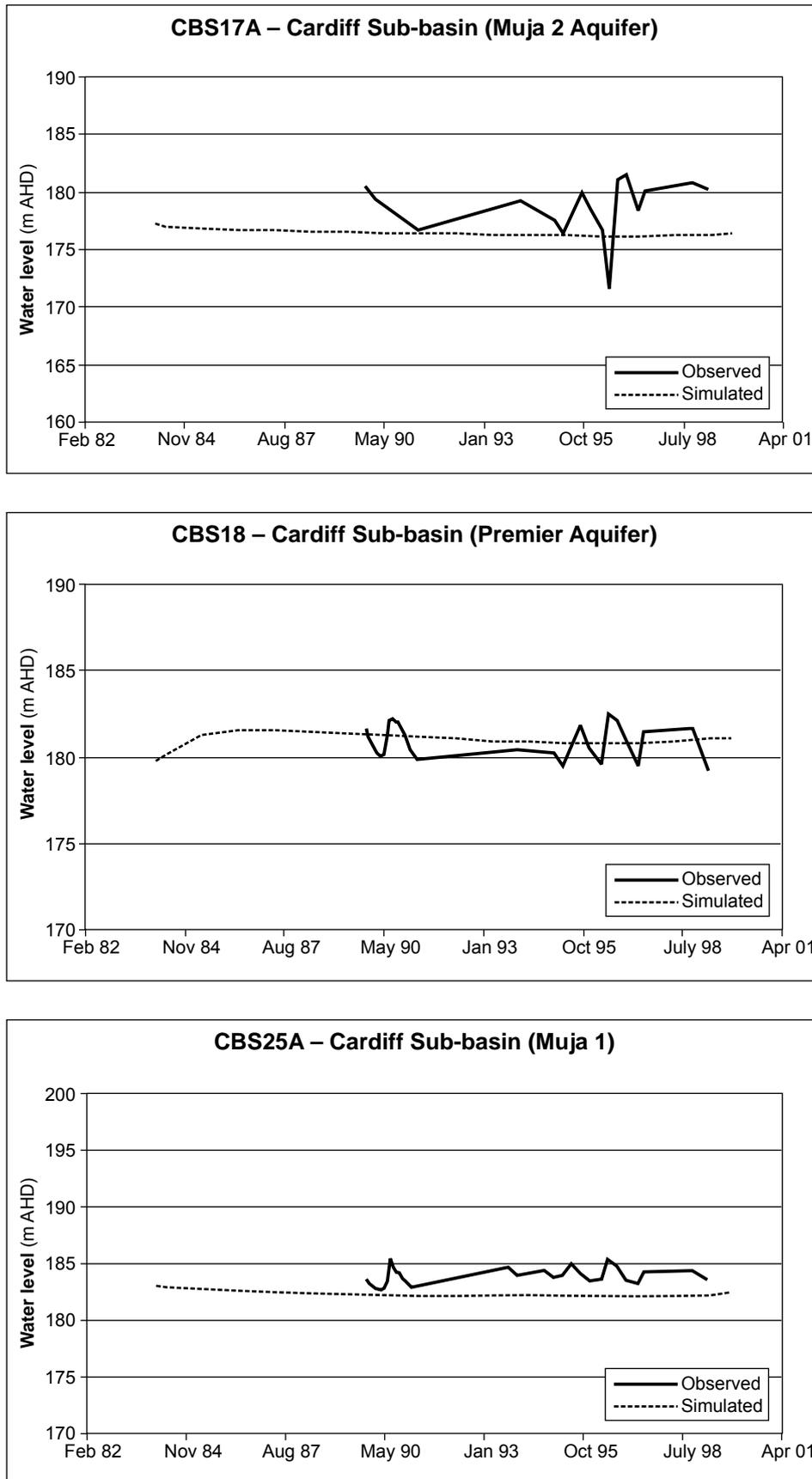


Figure 24. Calibration hydrographs (Set 4)

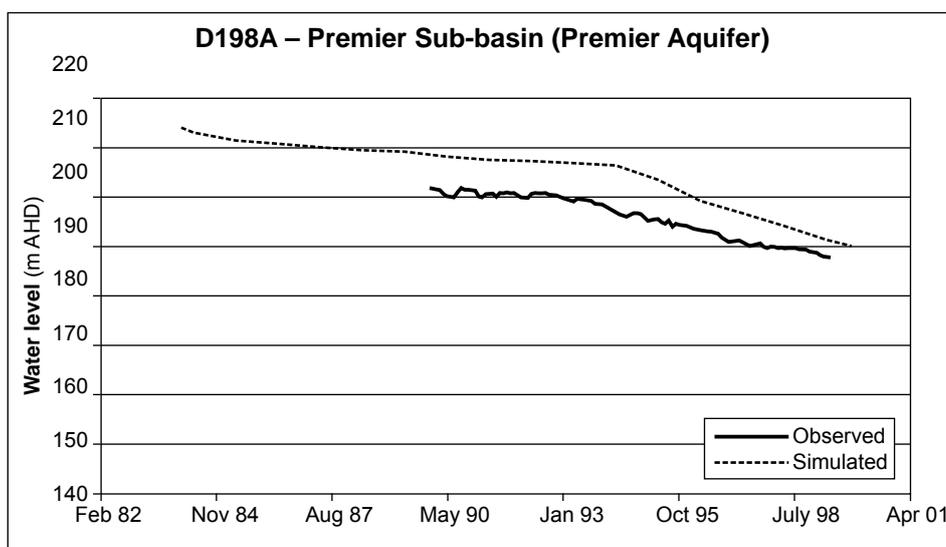
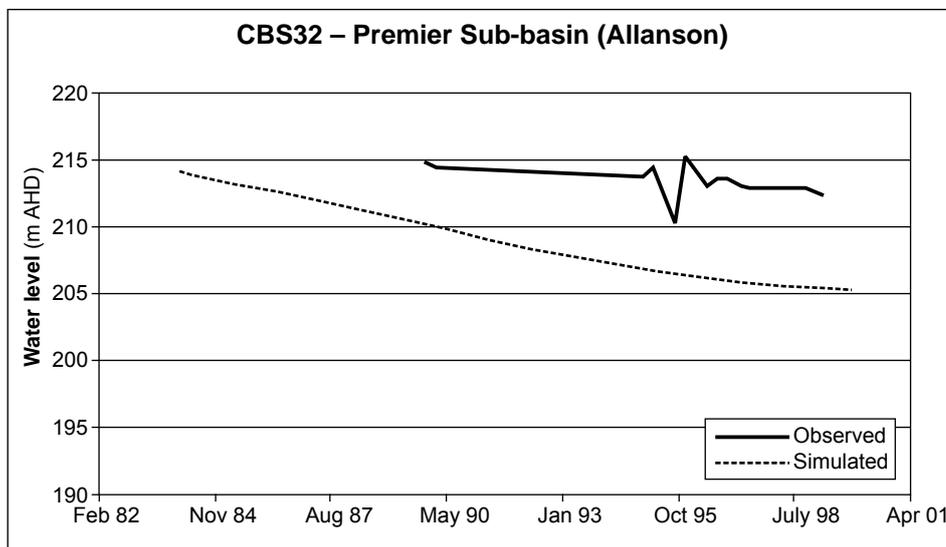
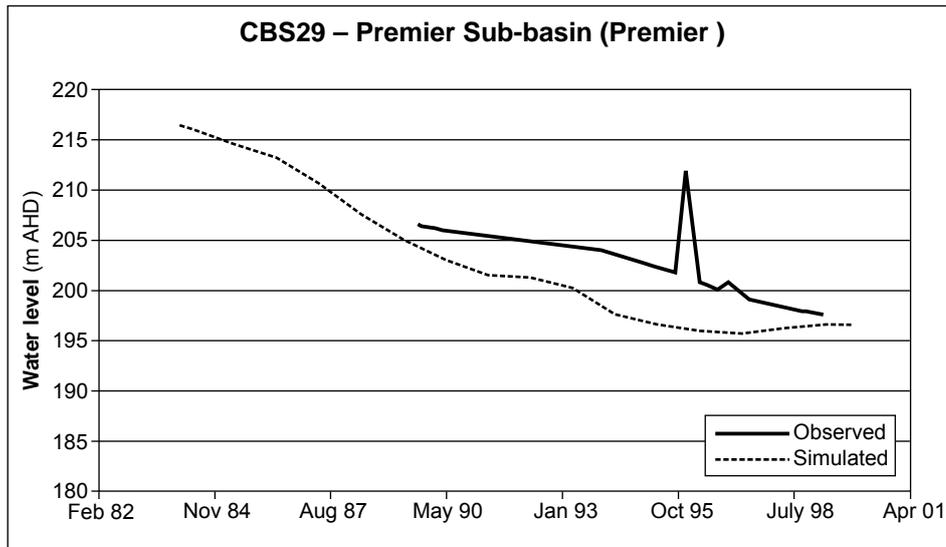


Figure 25. Calibration hydrographs (Set 5)

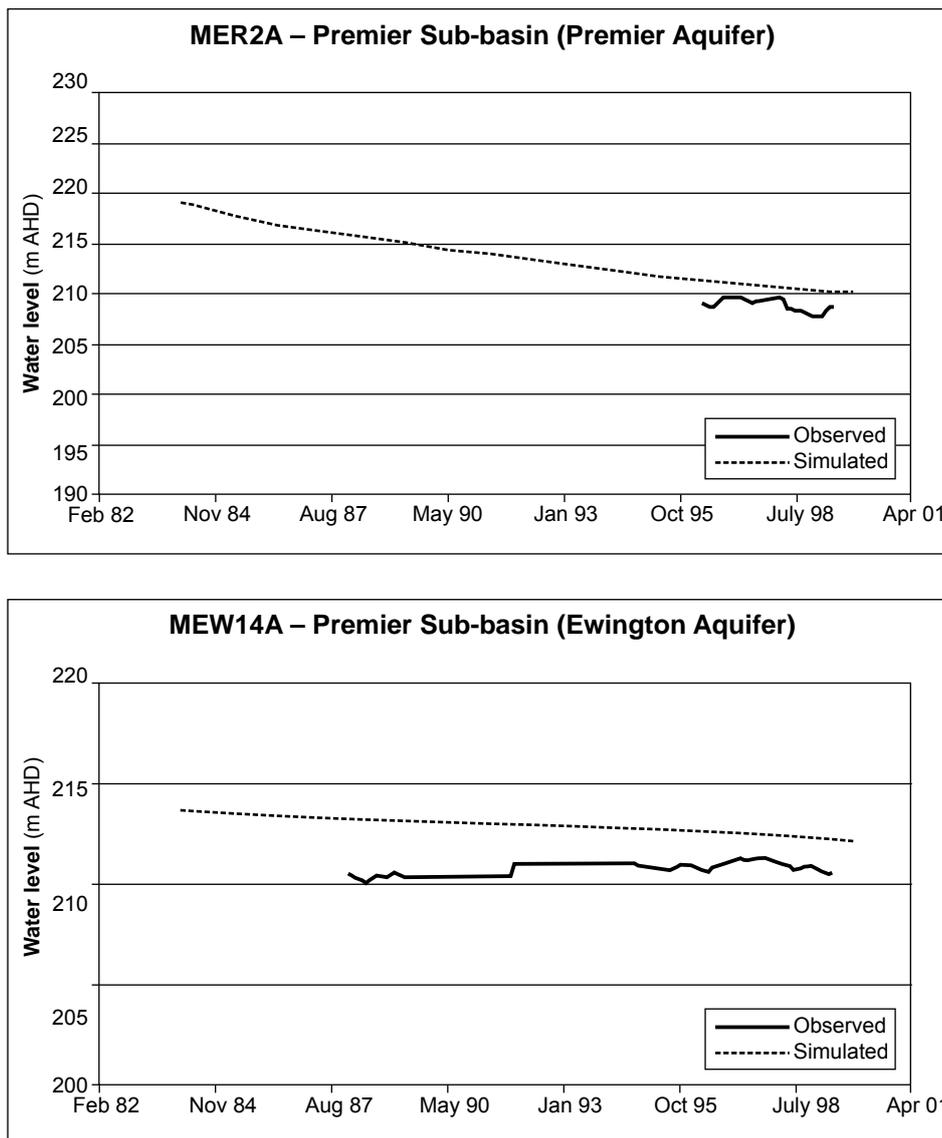


Figure 26. Calibration hydrographs (Set 6)

Table 9. Water balance components from the transient model

Component	Inflow (GL)	Outflow (GL)
Recharge	18.8	-
River	1.3	6.1
Wells	-	21.7
EVT	-	0.9
Total	20.1	28.7
Net storage change		-8.6

#### 4.3.5.3 Water balance components

A summary of the Collie Basin water balance components derived from the transient model is presented in Table 9. A flow chart illustrating the water balance of individual layers based on model output is provided in Appendix B. The water balance components are in general agreement with those determined analytically by Varma (2002).

#### 4.3.5.4 Potentiometric heads

Potentiometric heads for each aquifer at the end of the model calibration period as derived from the model are provided in Appendix D. The areas of significant drawdown show good comparison with areas of known past and present abstractions. The watertable declined significantly, especially along the South Branch river pools and near the subcrop zones of Muja 3 and the Premier Coal Measures, in response to groundwater abstraction at Western 2 and ACIRL wellfields. Significant drawdowns are also observed in the southern part of the Premier Sub-basin near the Muja mine.

The transient heads in Muja 1 are significantly reduced due to mine dewatering at Western 5 open cut mines as well as leakage from this layer to underlying layers as a result of large-scale groundwater abstraction in Muja 2 and Muja 3 layers. Groundwater levels in Muja 2 show the effects of groundwater abstraction from the ACIRL wellfield and Western 2 and Western 6 wellfields from both Muja 2 and Muja 3 layers, with a prominent cone of depression around the wellfields. A similar cone of depression is observed in the water levels of the Muja 3 layer.

In the Premier Coal Measures the water levels show a large cone of depression near the Cardiff South wellfield as well as the Western 2, Western 6 and ACIRL wellfields from which large-scale groundwater abstraction has occurred in the past. In the Premier Sub-basin, cones of depression are observed around the Ewington II and the Muja mines. Groundwater levels in the deeper layers (Allanson Sandstone, Westralia Sandstone, and Stockton Group) show large areas that have been affected by groundwater abstraction in the southern part of the Cardiff Sub-basin. In the Premier Sub-basin, significant drawdown is observed near the Shotts wellfield. Figure 27 shows contours of the difference between the steady state watertable and the transient watertable. The contours highlight areas where groundwater abstraction in the past has caused significant drawdowns.

The total volumetric difference between the modeled pre-mining and end of transient calibration watertable surfaces is estimated as 1600 GL. This equates to 240 GL of groundwater that has come out of the storage, adopting a specific yield of 0.15. About 150 GL of this volume applies to the Cardiff Sub-basin.

## 4.4 Sensitivity analysis

The purpose of sensitivity analyses is to quantify the uncertainty in the calibrated model caused by uncertainty in the estimates of aquifer parameters (Anderson & Woessner, 1991). Outcomes from a sensitivity analysis can also guide further data collection for model improvement.

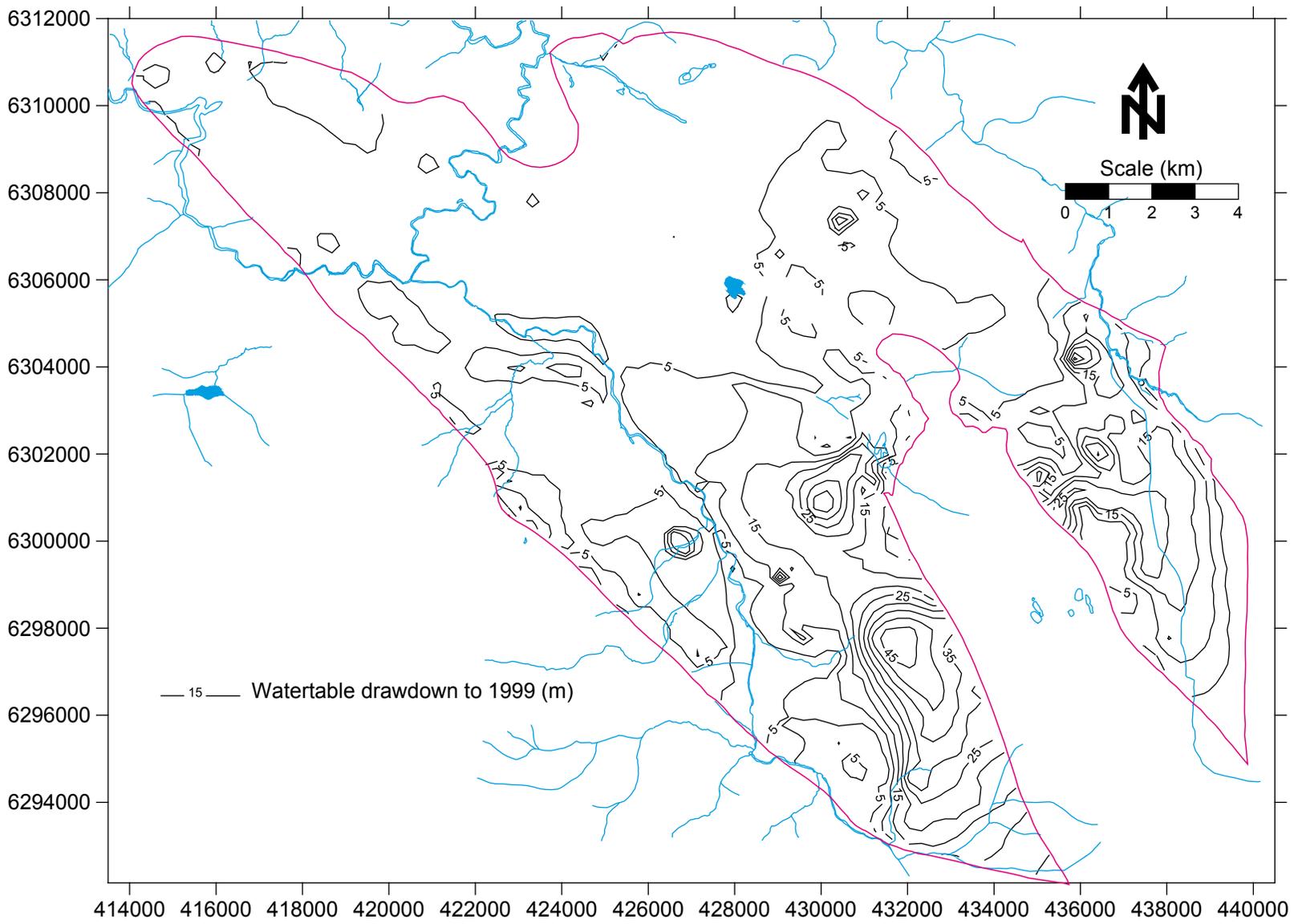


Figure 27. Watertable drawdown

Geo-Eng (2001) considered that for relatively small models, the sensitivity analysis procedure would include testing each parameter, for each layer, over the full range expected for that parameter. An analysis at this scale was not considered possible for the Collie Basin model due to the number of layers and the time required to run the model. Instead, a number of parameters that have been identified as sensitive (or uncertain) during model calibration, for important layers were analysed.

Geo-Eng (2001) determined that the most sensitive parameter for the layers tested is vertical hydraulic conductivity ( $K_z$ ) of the Muja 3 layer, with a 50% change in  $K_z$  producing an average head difference of 1.1 m. This is because significant groundwater abstraction occurs from the Muja 3 and the vertical hydraulic conductivity controls leakage from the overlying and underlying layers. Future investigations are required to obtain field data for comparison with the model calibrated  $K_z$  of the Muja 3 layer. The vertical hydraulic conductivity of the Muja 2 and Muja 3 layers also has significant influence on the time needed for groundwater to recover to a certain level if abstraction is stopped or reduced from the Muja 3 layer. The sensitivity analysis indicates that the model is less sensitive to changes in specific storage, with a 50% change in parameter value equating to an average 0.28 m head change in Muja 3 layer.

## 5 Prediction simulations

Stage I and Stage II of the modelling project consisted of development of a numerical 3D groundwater flow model of the Collie Basin. The main objective of Stage III of the modelling project is to test the ability of the model to predict the impacts of the changes in pumping stresses on the water levels and fluxes. For this stage, the following pertinent management issues were included in predictive simulations of the model:

- Groundwater discharge to Collie River;
- Aquifers storage (watertable) recovery in the Cardiff Sub-basin; and
- Western 5B mine void water level changes based on different streamflow diversion options.

The following table (Table 10) lists various scenarios for which recovery of water levels in the Collie Basin have been simulated using the Collie Basin Groundwater Flow Model.

Table 10. List of scenarios for prediction simulations

Scenario	Abstraction (GL/year)*				Other options	
	Cardiff South wellfield	Western 2 and Western 6 wellfield	ACIRL sumps	Premier Sub-basin	Pool supplementation	Recharge at 20 GL/year
Test 1	0	0	0	10.2	No	Steady
Test 2	0	0	0	10.2	Yes	Steady
Test 3	0	0	0	10.2	Yes	20% reduction over 50 years
Test 4	3.65	0	0	10.2	Yes	Steady
Test 5	3.65	8.75	0.73	10.2	Yes	Steady
Test 6	0	0	0	0	Yes	Steady

The recovery of water levels in WO5B mine void has been simulated for two options: one with 5 GL/year of streamflow diversion and the other without any streamflow diversion. Prediction simulations for recovery of water levels, based on abstraction and climatic scenarios, have been carried out for 50 years. For simulation of mine void water levels, prediction runs have been carried out for 20 years. There are two stress periods in each year corresponding to the wettest and the driest months.

In modelling recovery of the watertable, a common issue encountered is the re-wetting of dry cells. MODFLOW simulates the groundwater flow in the saturated zone only. If the watertable is present in the model layers other than the uppermost layer, the model cells above the watertable become 'dry cells' in MODFLOW. No flow takes

place in the dry cells and these cells are made 'inactive' in MODFLOW. In a situation where the watertable rises above the base of these dry cells, for example as a result of water level recovery due to reduced stresses, the dry cells must be allowed to be 'wetted' or activated so that storage changes in these dry cells can be taken into account. In the Collie Basin, there is a large area of dry cells (above watertable) in the Cardiff Sub-basin resulting from past abstractions. These dry cells would need to be re-wetted during watertable recovery. In the model, this re-wetting process has been accomplished by using the Block Centered Flow package-version 2 (BCF2). However, attempts to re-wet some dry cells caused numerical instability in MODFLOW, and these cells have been specified as non-rewettable in the model. The non-rewettability of these dry cells is believed not to have a considerable effect on the overall modelling results as they only occupy a small area.

## 5.1 Simulating water level recovery in Cardiff Sub-basin

Simulation of water level recovery has focused on the Cardiff Sub-basin, as in the Premier Sub-basin; mine dewatering is likely to continue over the long term. It is estimated that the past abstractions have caused a net storage change of 150 GL in the Cardiff Sub-basin and a replenishment equal to this volume will be required for complete recovery of the groundwater levels in the sub-basin. As the watertable recovers as a result of reduced abstractions, this storage deficit will progressively reduce until complete recovery or a new steady state is reached. Recovery will depend on various factors such as groundwater abstraction, any artificial recharge (eg by pool supplementation), and any climatic changes. Recovery has been assessed as a ratio of the volumetric difference between the present watertable and the predicted watertable, and the volumetric difference between the present and the pre-mining steady state watertables after a certain time period. Recovery has also been assessed in terms of watertable rise adjacent to the significant river pools.

### 5.1.1 Groundwater recovery in the Cardiff Sub-basin

The percentage recovery to the steady state condition in Cardiff Sub-basin is shown in Figure 28 for different scenarios of prediction simulations. Analysis of volumetric recovery for the Cardiff Sub-basin shows that a reduction of 20% rainfall recharge over 50 years (Test 3) will result in a slower recovery of watertable, with 77% recovery in 50 years compared to 93% if rainfall does not decline, assuming pumping takes place in the Premier Sub-basin only. Recovery will be severely affected if pumping continues in the Cardiff Sub-basin. Volumetric recovery for Test 2 scenario (having annual pool supplementation) shows no significant difference with the results of Test 1 scenario, ie without pool supplementation.

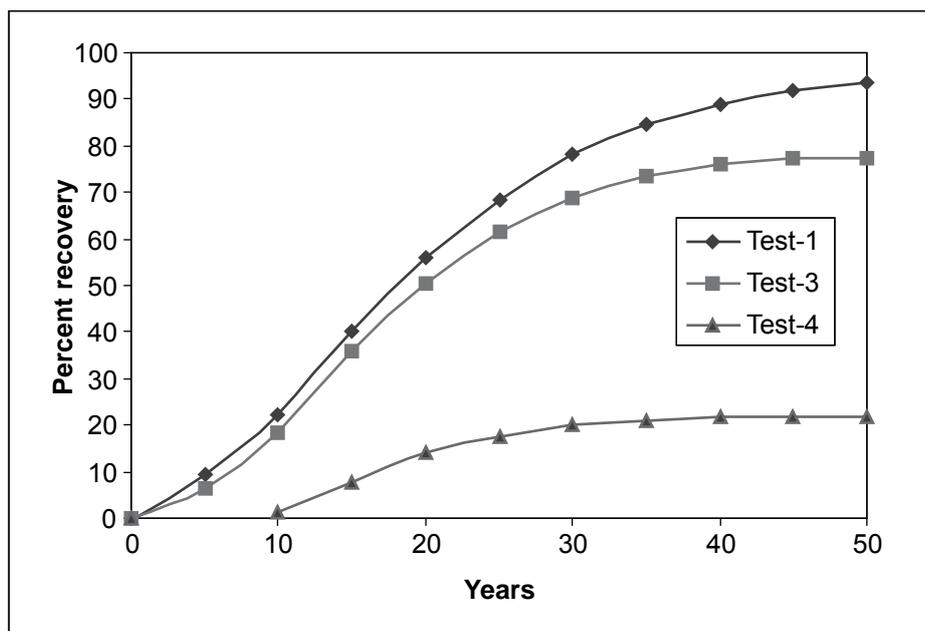


Figure 28. Volumetric recovery in Cardiff Sub-basin

## 5.2 Simulating Western 5B mine void water levels

The water level in WO5B mine void depends on the water balance of the void. Water inflow to and outflow from the void is expressed as:

$$\text{Inflow} = \text{Rainfall} + \text{Runoff} + \text{Streamflow Diversion}$$

$$\text{Outflow} = \text{Evaporation} \pm \text{Leakage}$$

The term leakage represents groundwater exchange between the void and the aquifer depending on head gradients, where the direction of flow is represented by a negative or positive sign. For small changes in the water level, the water level change in the void can be estimated by the following simple expression:

$$\Delta h = (\text{Inflow} - \text{Outflow}) / (\text{Area of surface water in void})$$

The calculation of all water balance components except leakage has been done outside the model using a spreadsheet. The model has been used to calculate the leakage, which depends on the head difference of the water level in the void and the adjacent groundwater level. The methodology is similar to the one developed for simulating water levels in the river pools (Appendix A), with the difference that the void cells have been specified with general head conditions instead of river condition as in the pools. Some data such as void dimensions and surface water catchment characteristics have been sourced from Dames and Moore (1996).

This methodology requires iterations to achieve a converged solution. To do so, an initial water level (constant head) was specified in the void, and the model-generated transient leakage was input into the spreadsheet water balance model. A new transient water level was obtained for the void from the spreadsheet model that was fed back

into the model as transient general heads in the void, and an updated leakage was obtained. By repeating this procedure, a converged leakage and water level in the void was finally obtained. Figure 29 illustrates the iterative procedure applied to obtain water levels in the void for the condition of no streamflow diversion into the void. The solution converged at the 7th iteration. Hence the water levels represented by Iteration 7 is the predicted water level in the void over 20 years.

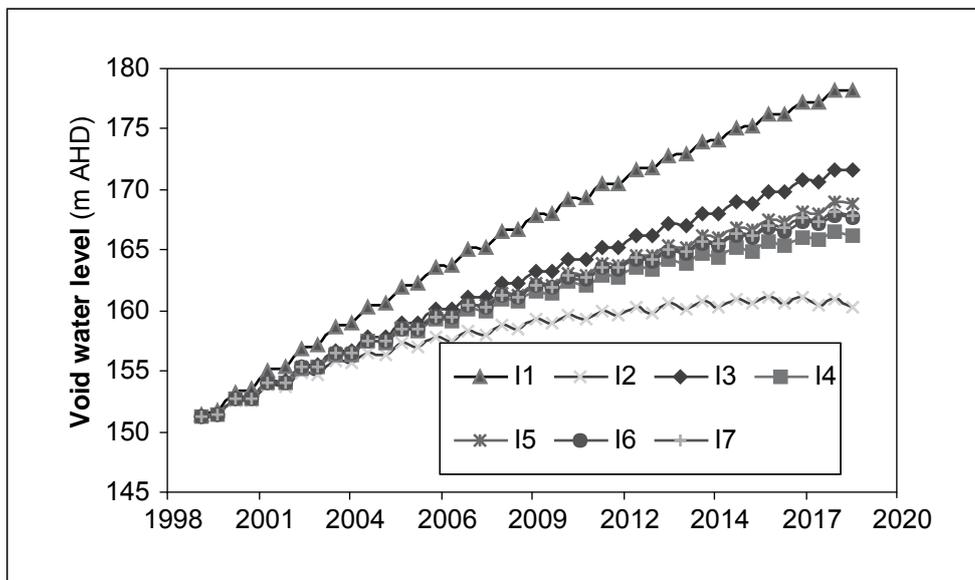


Figure 29. Iterative computation of W05B void water level

Recovery of water level in void 5B has been predicted for two conditions: (a) no streamflow diversion, and (b) having streamflow diversion of 5 GL/year. Pumping flows in the Cardiff and Premier Sub-basins are 0 and 10.2 GL/year, respectively. Water level recovery in void Western 5B based on the two options is shown in Figure 30. Simulation shows that without streamflow diversion, the water level in the void reaches about 167 m AHD in 20 years, however streamflow diversion significantly enhances the recovery of water level in the void. The model predicts that the water level in the void will reach the overflow level (190 m AHD) in 5 years. The fluctuations of water level are due to seasonal changes in rainfall and evaporation. In modelling streamflow diversion, it is assumed that maximum streamflow diversion takes place in August and that no streamflow takes place in the dry season. This condition results in the fluctuations of water level as seen in Figure 30. The streamflow diversion has a noticeable effect on water level changes in the void, and consequently the seasonal effect of rainfall and evaporation has become insignificant under this option.

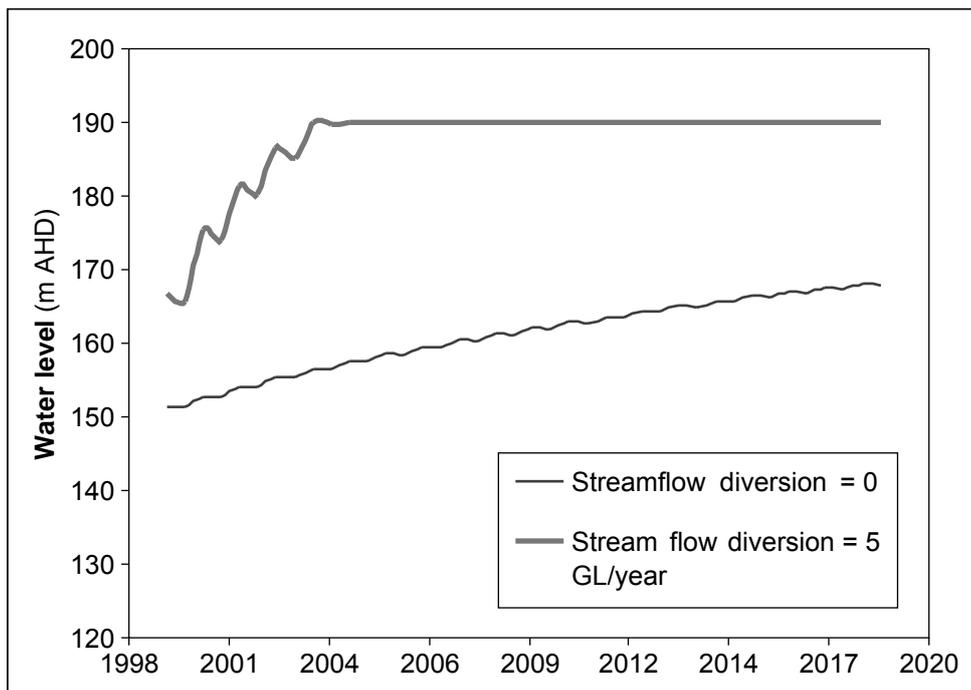


Figure 30. Water level recovery in WO5B void

### 5.3 Groundwater discharge to the Collie River

Groundwater discharge as baseflow to the rivers and creeks of the Collie Basin under different modelling scenarios is given in Table 11.

Table 11. Groundwater discharge to rivers

Years	Groundwater discharge to rivers (GL/year)					
	Test-1	Test-2	Test-3	Test-4	Test-5	Test-6
5	6.6	6.6	6.6	6.5	6.0	6.6
10	7.5	7.6	7.4	7.3	5.9	7.9
20	9.4	9.4	8.8	8.4	5.7	11.5
30	10.4	10.4	9.5	8.8	5.4	-
50	11.3	11.3	9.4	8.8	4.9	-

Modelling shows that under scenarios of no pumping in the Cardiff Sub-basin, the groundwater discharge to the Collie River recovers from about 6 GL/yr to 11.3 GL/yr which is about 70% of the pre-mining steady state discharge. Recovery would be more if there were no pumping in the entire basin.

## 6 Model assumptions and limitations

### 6.1 Data gaps and assumptions

A number of important data gaps that have affected the development and accuracy of the Collie Basin groundwater flow model are identified and listed below.

- Although, mining and hence dewatering in the basin has occurred since 1898, records of abstraction are only available since 1984.
- A simplifying assumption for the generation of data sets is that the stratigraphic relationships are consistent throughout Collie Basin.
- There is a lack of data on both water levels and stratigraphy at depths in the basin.
- Historical groundwater abstraction data for the period 1984 to 2006 may be incomplete. Mining company reports (eg Western Collieries Ltd, 1991) indicate that detailed groundwater abstraction records exist from 1984, but as yet only incomplete paper records have been sourced. An incomplete knowledge of groundwater abstraction will have an effect on accuracy of the model particularly at small stress periods.
- The shape of the river and pool beds is not well known. A longitudinal survey exists along the centreline of the Collie River South Branch pools, but cross-sectional profiles would be valuable in providing information of the profile and capacity of each of the pools. In addition, little data exists for river bottom elevation and profile along the Collie River East Branch. Available data consists of surveys in the vicinity of existing stream gauging stations. Records of river stages are available at very few locations within the basin.
- It is considered that there is an incomplete understanding of the hydraulic characteristics of the Nakina Formation and surficial units. For example, the presence of low-permeability fossil soil layers on top of the Permian sediments may impede the flow of groundwater to the subcropping Permian aquifers. There is probably insufficient data at this stage to create detailed zone maps for each layer for calibration purposes, or to represent fine-scale features that may be locally important.
- A number of input data required for the modelling process were either unavailable or incomplete. In order to produce a realistic and robust model a number of assumptions and inferences for both the conceptual and mathematical models have been made. These include the following:
  - a. A simplifying assumption in the model is that stratigraphic relationships are consistent throughout the Collie Basin, and the hydraulic properties within individual layers are consistent within the different zones within a layer;
  - b. Rainfall recharge is the dominant form of recharge to the basin sediments;

- c. A number of assumptions had to be made on how to apply abstraction to bores where either the data was available on an annual basis, and had to be applied monthly, or the abstraction depth was only partially known;
- d. The river stage values specified in the current model are assumed.

## 6.2 Model limitations

In addition to the assumptions made, a number of limitations exist, both in the data available to produce a model, and in the model itself. The model may be improved with ongoing work, as more data becomes available. The limitations and uncertainties are listed below:

- The spatial distribution of rainfall recharge across the basin is coarse at this stage, although the overall water budget agrees with the current literature. Since rainfall recharge is the major source of groundwater, it has impacts on the watertable configuration as well as recharge to the aquifers, and hence is an important parameter. Effects of surficial soil types and vegetation coverage on recharge have not been considered in the model.
- Due to the unavailability of relevant observation data, the hydraulic conductance of riverbed sediment in the model for most parts of the Collie River, cannot be supported or calibrated. In addition, the shape of the river is not well known. Also, limited data exist for riverbed elevation along the Collie River East Branch. Available data consisted of surveys only in the vicinity of existing stream gauging stations and some river pools.
- Not all of the pools of the Collie River South Branch and East Branch have groundwater observation bores drilled next to them. The conductance values for the river pools in the model were derived from simple water balance analyses (Varma, 2002), and it is not possible to confirm or calibrate them in the model at this stage. An improved understanding of surface water-groundwater interaction at each pool would require a groundwater observation bore at each site and regular recording of pool water levels. Additionally, lithological profiles derived from drilling would provide valuable information on the vertical profile at each site.
- There is a lack of data, both water level and stratigraphic, at depths in the Permian sediments. Therefore, the deep aquifers, from the Premier Coal Measures (Model Layer 5) downwards, cannot be accurately calibrated. At this stage, achievement of calibration in deeper layers is being considered on the basis of: head contours in these layers being in general agreement with the conceptual understanding, the water balance of the basin as whole, and expression of the stresses in these layers on the watertable.
- An individual layer within the model will comprise a number of hydrostratigraphic units (sandstone, siltstone, and coal), but the properties of these individual units have been homogenised by combining them in a single model layer. Vertical head gradients within a layer, especially in areas of groundwater pumping where gradients

may be steep, will not be represented in the model. However, the size of model does not allow for extremely fine vertical discretisation for simulation of such conditions.

- The effects of faults on groundwater flow in the basin are not well known. Faults are represented in the model as horizontal flow barriers. In some cases, however, it was observed that adjusting the permeability of faults (flow barriers) affected model results, and in some cases improved calibration. Further work may be required to study the effects of faults for their accurate representation in the model.
- There is a lack of observed time series water level data from the Premier Sub-basin. However, the comparison of observed and simulated heads for some shallow watertable bores in the Premier Sub-basin shows relatively good correlation. This indicates that, at least for the upper part of the sequence, the Premier Sub-basin can be considered to be reasonably well calibrated.
- The model is not accurate in the Western 7 area possibly due to large vertical gradients in the area. Calibration could improve by addition of model layers.

## 7 Conclusions

A three-dimensional groundwater flow model has been developed for the Collie Basin using MODFLOW and GMS under a three-stage program. Prior to construction of the numerical model, a comprehensive review of available literature was undertaken to enable an understanding of the hydrogeologically and hydrologically significant features of the Collie Basin. Data were interpreted to produce surfaces, isopachs, and cross-sections of the nine units that represent the sedimentary sequence of the basin.

Data collected during this project include stream levels and flows, rainfall and evaporation data, groundwater levels, bore construction, abstraction and screened intervals. These have been incorporated into a number of standardised data sets for input to the model.

As a part of Stage I study, the use of MODFLOW for construction of the Collie Basin model was recommended. It is believed that no single modelling package contains all of the features desirable for development of the Collie Basin model. However, MODFLOW run through the graphical user interface such as GMS and MODFLOW-SURFACT both have features that are desirable for construction of the Collie Basin model. GMS-MODFLOW was however selected as the most appropriate tool for developing the model.

The model has been calibrated under steady state and transient conditions with available data. The steady state water balance (which was based on the assumption that the initial groundwater system was unstressed by groundwater abstraction) indicates that the magnitude of the water balance components as derived from the model is reasonably accurate. The average absolute head residual for the steady state calibration is 1.64 m, which is considered to be acceptable for a regional scale model. In areas where no observation bores are available, the simulated watertable configuration matches qualitatively with the conceptual watertable. In addition, flow directions across the entire basin also match those indicated in the literature.

The model was calibrated under stressed conditions from 1984 to 1999. The transient water balance indicates that the volumes of recharge to the model, the groundwater discharge to the Collie River and the water released from storage are close to published figures. In addition, the simulated heads match the observed heads at most bores examined.

Sensitivity analyses were undertaken on storage coefficients and hydraulic conductivities of Nakina, Muja 2 and Muja 3 Formations by Geo-Eng (2001). The vertical hydraulic conductivity of the Muja 3 layer was identified as the most sensitive parameter for the cases considered. It is considered that recent changes to the model are unlikely to influence the sensitivity of the parameters.

The Collie River has been simulated in the model using the River Package in MODFLOW. Model output indicates that the river cells appear to work properly under steady state and transient conditions. A reasonable response between river-groundwater interaction and groundwater abstraction has been obtained and a

methodology for modelling surface water-groundwater interaction has been established using the River Package.

The validity of the model is evidenced in the following aspects:

1. Major groundwater recharge and discharge zones have been simulated in the model, which generates an overall water balance (recharge for entire domain and recharge for each sub-basin) that is consistent with those reported (eg CWAG, 1996; Varma, 2002). The watertable for the steady state condition also matches the conceptual watertable.
2. Water balance components and flow patterns for each model layer are considered to be conceptually correct. The model shows that shallow groundwater discharges into Chicken Creek, Boronia Gully Creek and Collie River East Branch in the Premier Sub-basin and into Collie River and South Branch in the Cardiff Sub-basin. Groundwater flow directions in deeper layers are consistent with those previously reported (eg Moncrieff, 1993).
3. Satisfactory agreement has been obtained between simulated and measured hydrographs for the monitoring bores in Muja 2 and Muja 3 model layers, from which most of the groundwater abstraction occurs. As the specific storage used in the model is within the previously estimated range ( $\sim 10^{-5}$  to  $10^{-6}$ /m; Geo-Eng, 2000) it would appear that the conceptual model is correct. This is demonstrated by the good agreement between the modeled and the observed drawdowns. There are, however, discrepancies in observed and simulated hydrographs from the Muja 3 layer in the Western 7 area. Calibration has not been achieved in this area possibly due to the significant vertical hydraulic gradient within the Muja 3 layer that cannot be simulated in the model using a single layer. Splitting of the Muja 3 layer into two layers could enable better calibration in this area.
4. Under stress conditions, the simulated watertable configuration for 1999 is in general agreement with the reported data, especially in the Cardiff Sub-basin. This indicates that the vertical flow through the layers is correctly simulated in the model under pumping conditions. However, at local scales discrepancy between simulated and observed watertable elevations occur. This may be due to local variations in recharge and geology that have not been simulated in the model.
5. The River Package is numerically stable and performs correctly as indicated by the prediction runs.

Several prediction simulations have been carried out using the model to test the ability of the model to predict, with reasonable confidence, the impact of abstraction on groundwater levels in the basin. The results of the predictive simulations are in agreement with results of previous work in the basin.

One of the objectives of the modelling program was to provide an *'Improved understanding of ... sustainable yields of individual sedimentary units.'* The definition of sustainable yield for the Collie Basin is a management consideration and has not yet been established. Generally, the sustainable yield is *'The groundwater extraction regime, measured over a specified planning timeframe, that allows acceptable levels*

*of stress and protects dependent economic, social, and environmental values*'. Hence, the sustainable yield is a volume that is considered within an overall management framework. It takes into account the volume of groundwater that is replenished annually by recharge and is essentially the maximum rate of abstraction that will not cause continued depletion in storage. The current model shows that on a basin scale, about 20 GL of replenishable recharge takes place annually. However, the actual sustainable yield will depend on economic, social and ecological constraints.

For the predictive simulations, the following pertinent management issues were assessed by the modelling runs:

- Groundwater discharge to Collie River;
- Aquifers storage (watertable) recovery in the Cardiff Sub-basin; and
- Western 5B mine void water level changes based on different streamflow diversion options.

Analysis of volumetric recovery for the Cardiff Sub-basin shows that about 90% recovery will be completed in 50 years provided long-term average rainfall was maintained. Recovery will be severely affected if pumping continues in the Cardiff Sub-basin.

Recovery of water level in Western 5B void has been predicted for two conditions: (a) no streamflow diversion, and (b) having streamflow diversion of 5 GL/year and assuming no pumping in the Cardiff Sub-basin. Simulation shows that without streamflow diversion, the water level in the void reaches about 167 m AHD in 20 years (from about 150 m AHD at the end of mining), however, streamflow diversion significantly enhances the recovery of water level in the void. The model predicts that the water level in the void will reach the overflow level (190 m AHD) in 5 years with streamflow diversion.

Modelling shows that under scenarios of no pumping in the Cardiff Sub-basin, the groundwater discharge to the Collie River recovers from about 6 GL/yr to 11.3 GL/yr which is about 70% of the pre-mining steady state discharge. Recovery would be more if there were no pumping in the entire basin.

The model development has facilitated the consolidation of existing conceptual knowledge on the Collie Basin hydrogeology. It is considered that the model will allow the objectives of the project to be met.

It is recommended that the model be used as a tool to provide assessments with respect to the following:

- Assessing the regional impacts on the water levels and groundwater discharges to the river and creeks as a result of pumping;
- Providing estimates of groundwater level recovery periods under different scenarios of pumping;
- Studying the groundwater-river interaction at river pools;

- Evaluating and comparing options for enhancing recovery of groundwater levels including artificial recharge;
- Establishing the water balance of the open cut mine voids in the basin based on a number of options of streamflow diversion volumes.

The model will form a valuable platform from which robust management initiatives and plans can be formulated. The Collie Basin is structurally complex, and relatively little is known of groundwater conditions within the basin, especially at depth. Interpretation of model outputs for above mentioned applications should therefore take this into account. The data assumptions and limitations of model have been stated in the earlier sections and provide a direction for future refinement of the model.

## 8 Bibliography

- Anderson, M. P. & Woessner, W.W., 1991, *Applied Groundwater Modelling – Simulation of Flow and Advective Transport*, Academic Press, San Diego, California.
- Aquaterra, 1999, *Cardiff Sub-basin Conceptual Model*, compiled by Middlemiss, H. & Hall, J., Report to Water and Rivers Commission.
- Australian Groundwater Consultants, 1987, *ACIRL Mining Trials, Collie, WA, Report on the Hydrological Studies and Dewatering*.
- Australian Groundwater Consultants, 1985, *South West Power Station, Raw Water Supply Borefield*.
- Australian Groundwater Consultants, 1984, *Muja Power Station, Stage D Water Supply, Cardiff-South Bores, Completion Report*, two volumes.
- Australian Groundwater Consultants, 1983, *Overburden Dewatering Bores for the Mining Research Project, Collie, WA*.
- Australian Groundwater Consultants, 1982, *Mining Research Project, Collie, Dewatering System Designs*, Revised Dec. 1982.
- Australian Groundwater Consultants, 1981, *Muja Power Station Water Supply, Phase 3 Groundwater Study*, two volumes.
- Australian Groundwater Consultants, 1980a, *Mining Research Project, Collie, Hydraulic Studies*.
- Australian Groundwater Consultants, 1980b, *Muja Power Station, Stage C Water Supply, Shotts Production Bore Program*.
- Australian Groundwater Consultants, 1978, *Muja Power Station Water Supply, Phase 2 Groundwater Study*, two volumes.
- Brigham Young University, 2001, *GMS v3.1, Reference Manual*, Brigham Young University – Environmental Modeling Research Laboratory.
- Bowman, S., 1998, *Collie Pit Void Surface Water Allocation*, Water and Rivers Commission Technical Report (Unpublished).
- Chamberlain, N. G., 1947, *Preliminary report on the Geophysical Survey of the Collie Basin*: Australian Bureau of Mineral Resources, Report 1.
- CSIRO Land & Water, April 1999, *Estimation of Groundwater Residence Times in the Collie Basin Using Carbon-14 Activity and CFC Concentrations*.
- Collie Water Advisory Group, 1996, *Strategies for Water Resource Management in the Collie Basin*, coordinated by: Department of Resources Development.
- Collie Water Advisory Group, 1999, *Collie Basin Water Resource Management – Reconsideration of Long and Short Term Strategies*, coordinated by: Department of Resources Development.

- Dames & Moore, 1995, *Collie Basin Hydrogeological Monitoring for the Department of Resources Development on Behalf of the Collie Water Advisory Group*.
- Dames & Moore, 1997, *Collie Basin Groundwater Resource and Aquifer Review to June 1996*.
- Dames & Moore, 1995, *Collie Basin Hydrogeological Monitoring for the Department of Resources Development on Behalf of the Collie Water Advisory Group*.
- Dames & Moore, 1996, *Proposed Closure Criteria for the WO5 Mine*, for Western Collieries Limited.
- Dames & Moore, 1998a, *Collie Basin Production / Monitoring Summary (July 1997 to June 1998)* for Western Power Corporation.
- Dames & Moore, 1998b, *Ewington 2 Mine – Dewatering Design for the Griffin Coal Mining Co. Pty Ltd*.
- Dames & Moore, 1999, *Collie Basin Production / Monitoring Summary (July 1998 to June 1999)* for Western Power Corporation.
- Geo-Eng, 2000, *Stage 1 – Data Search, Literature Review and Conceptualisation for a Three Dimensional groundwater flow model of the Collie Basin*, Geo-Eng Report GEP 16/00, produced for Water and Rivers Commission, WA.
- Geo-Eng, 2001, *Collie Basin 3D Groundwater Modelling – Stage 2*, Geo-Eng Report GEP 14/01, produced for Water and Rivers Commission, WA.
- Groundwater Resource Consultants, 1984, *The Griffin Coal Mining Company Limited, Muja Opencut Dewatering Programme, Results of PRB 14 Aquifer Testing*, Accession Report 549.
- Groundwater Resource Consultants, 1983a, *The Griffin Coal Mining Company Limited, Muja Opencut Dewatering Programme, Dewatering Installations*, December 1983. Production Bores.
- Groundwater Resource Consultants, 1983b, *The Griffin Coal Mining Company Limited, Muja Opencut Dewatering Programme, Completion Report Production Bore 4-A*.
- Hayes, R. J. and Garnaut, G., 1981, *Annual rainfall characteristics of the Darling Plateau and the Swan Coastal Plain*, Public Works Dept. of WA Report WRB 3.
- Henderson, N., 1999, *Surface Water and Groundwater Quality and Water Balance Studies at Long Pool, Collie Basin*, Curtin University.
- Hsieh, P. A. & Freckleton, J. R., 1993, *Documentation of a Computer Program to Simulate Horizontal-flow Barriers using the U. S. Geological Survey's Modular Three-dimensional Finite-difference Ground-water Flow Model*, U. S. Geological Survey Open-File Report 92-477.
- Kevi, L., 1990, *Revised Bouger Anomaly Map of the Collie Basin and Adjoining Areas*: Western Australian Geological Survey, Record 1990/9.
- Layton Groundwater Consultants, 1982, *Bore Completion Report, Pressure Relief Bore 12*, for Griffin Coal Mining Company Limited.

- Layton Groundwater Consultants, 1980, *Dewatering Bore No. 3 (DWB3) Completion Report*, for Griffin Coal Mining Company Limited.
- Layton Groundwater Consultants, 1979, *Dewatering/ Depressurising Requirement, Muja Open Cut*, for Griffin Coal Mining Company Limited.
- Leake, S.A. & Claar, D.V., 1999, *Procedures and Computer Programs for Telescopic Mesh Refinement using MODFLOW*, U.S. Geological Survey Open-File Report 99-238.
- Le Blanc Smith, G., 1993, *Geology and Permian Coal Resources of the Collie Basin, WA*: Geological Survey of Western Australia, Report 38.
- Lord, J. H., 1952, *Collie Mineral Field*, Western Australia Geological Survey, Bulletin 105, Part 1.
- Low, G. H., 1958, *Collie Mineral Field*, Western Australia Geological Survey, Bulletin 105, Part 2.
- Luke, G. J., Burke, K. L. and O'Brien, T. M., 1988, *Evaporation data for Western Australia*, Western Australian Dept. of Agriculture Tech. Rep. 65
- McDonald, M. G. and Harbaugh, A. W., 1988, *MODFLOW, A Modular Three-Dimensional Finite Difference Groundwater Flow Model*, U.S. Geological Survey, Open-file report 83-875.
- Mauger, G. W., 1996, *Modelling dryland salinity with the M.A.G.I.C. system*, WRC Report WRT 7.
- Mohsenzadeh, H. A., 1998, *Collie Basin Watertable Monitoring Bores, Drilling Results*, Water and Rivers Commission, Hydrogeology Report Number HR119.
- Moncrieff, J. S., 1991, *Collie Basin Shallow Project*, Bore Completion Reports, Geological Survey of Western Australia, Hydrogeology Report No. 1991/8 (unpublished).
- Moncrieff, J. S., 1993, *Hydrogeology of the Collie Basin, WA*, Geological Survey of Western Australia, Report 34, pp129-153.
- Murray Darling Basin Commission (MDBC), 2001, *Groundwater Flow Modelling Guideline*: Report by Aquaterra Consulting Pty Ltd.
- Office of Energy, 2003, *Energy-Western Australia*, Government of Western Australia, February 2003.
- Spitz, K. & Moreno, J., 1996, *A Practical Guide to Groundwater and Solute Transport Modeling*, John Wiley & Sons Inc.
- Varma, S., 1997, *Effect of Groundwater Abstraction in the Cardiff Sub-basin on Pools of the Collie River South Branch*, Water and Rivers Commission, Hydrogeology Report Number HR97.
- Varma, S., 2002, *Hydrogeology and Groundwater Resources of Collie Basin, Western Australia*, Water and Rivers Commission, Report HG5.
- Western Collieries Ltd, 1991, *Composite Groundwater Abstraction Report, Collie Basin Operations*, Report No. 156.

# Appendix A

## Modelling Surface Water and Groundwater Interaction

Q Zhang

### 1. Introduction

One of the major objectives of constructing the Collie Basin groundwater flow model is to simulate the surface water and groundwater interaction at pools to enable assessment of the impacts of groundwater abstraction on pools and study the effectiveness of any artificial supplementation. The numerical model is expected to show the interactions between groundwater and the pools for different hydrological conditions, especially simulating the process of drying and re-wetting of the pools in response to adjacent groundwater level changes and other water balance components. A literature review has been done to select the most appropriate approach to simulate this complex process.

### 2. Physical background

The Collie River is a key feature of the groundwater flow model of the Collie Basin. The river is assumed to be in contact with the regional groundwater system. Based on some literature and anecdotal information, an assumption is made that the river was in most segments influent and received groundwater discharge prior to the mining activities in the Collie Basin. Mine dewatering has subsequently lowered the regional watertable significantly and streamflow does not occur in summer in most of the upstream parts of the river and water is contained only in isolated pools. Some of the pools intersect the watertable, whilst at some others the watertable has been significantly lowered and is below the base of the pools. As a result of streamflow, the pool levels rise, but soon after cessation of winter rain the levels decline as a result of evaporation and leakage.

### 3 Modelling surface water-groundwater interaction

The Collie groundwater flow model is constructed using MODFLOW (originally developed by McDonald and Harbaugh, 1988). Various packages have been developed for MODFLOW to account for the influence of surface water bodies. A comparison of the packages is given as follows:

#### 3.1 River package

This package refers to the River Package in McDonald and Harbaugh (1988). It simulates the effects of flow between a surface water and groundwater system. A finite difference cell containing a river reach is treated as a river cell. A stage representing the water level in the river is assigned to the river cell. If the calculated head at the river cell

is higher than the stage, groundwater flows into the river. If the calculated head at the river cell is lower than the stage, water flows from the river to the groundwater system. The flow rate is calculated as the product of the riverbed hydraulic conductance and the head difference between the groundwater and the stage. If the groundwater head drops below the river bottom elevation, ie an unsaturated zone occurs between the watertable and the riverbed, the flow rate is calculated as the product of the riverbed hydraulic conductance and the water depth in the river. Surface water balance and streamflow in the river are not taken into account. This package is simple and numerically stable. Parameters needed to use this package include river stage, riverbed elevation and riverbed conductance. Some developments have been made to the original version so that stage and riverbed conductance can be defined as time-dependent parameters for a transient simulation. This package requires that a stage higher than the riverbed elevation must always be specified, ie the river cell will never go dry mathematically.

### 3.2 Stream-aquifer package

Prudic (1989) presented a modelling approach (Stream-aquifer Package) to simulate groundwater-river interaction. Streamflow is taken into account when calculating leakage from the stream to the groundwater system. Recharge to the aquifer from stream reach ceases when all the streamflow in the upstream reaches has leaked into the aquifer and the stream is dry. In addition, the stage in each reach can be computed within the package using the Manning formula under the assumption of a rectangular stream channel. The Stream Package is useful if there are great changes in river flow that will affect significantly the river stage, eg there are many diversions and tributaries that change the flow. Water balance calculation for each reach is a step forward compared with the River Package. However, this surface water balance calculation will cause problems when applied to the Collie River South Branch. Streamflow can only occur between the pools when the stage rises above cease-to-flow elevation. When the stage is below the cease-to-flow elevation, a significant amount of water would still be in the pool even if there is no streamflow (the stream reaches between the pools are dry). Leakage between the pools and groundwater still occurs in this case as long as the pool contains water. However, the Stream Package will consider that pool leakage is immediately unavailable because the upstream reach is dry and this is inappropriate for the Collie situation. Leakage from the pools should not be limited only by the streamflow in the upstream reach. The volumes of the pools range between 379 m<sup>3</sup> (Cox Pool) to 32 224 m<sup>3</sup> (Long Pool), and it should take some time for the pool to become dry even if there is no inflow water to the pool. Therefore, this package alone is not suitable for the Collie River South Branch.

### 3.3 RES1 package

Fenske et al. (1996) developed a computer program (RES1) to simulate leakage from reservoirs. RES1 package is useful when simulating the effects of the change of reservoir water surface area due to change of water level in the reservoir (and hence change of inundation area). In order to simulate the effects of the change of water surface area in the reservoir, the geometry and shape of the reservoir (ie detailed information on reservoir bottom elevation) must be input into the model and represented

by many reservoir model cells. Therefore, if RES1 were to be used to simulate the Collie River pools, the cell size around the pools should be around 5 m since the pool size is only ~ 50 m wide or less. Moreover, detailed information on the pool's geometry and shape is unavailable. Many uncertainties and unknowns will be introduced if the pool is discretised into many cells. Another problem is that when the groundwater head at a reservoir cell drops below the reservoir bed elevation, the reservoir cell is turned off and cannot be turned on again when the watertable rises. Considering the situation of the Collie pools, it is expected that when the watertable recovers to a certain level, pools should gain water from the groundwater system and the model should simulate this. Compared with the River Package, the only difference is that RES1 can calculate and update the reservoir area as it expands or contracts in response to changes in reservoir stage. This calculation, however, is based on the user-specified stage change curve for the simulation period. This does not apply to the pools where stage change is unknown and is to be modeled. Solid benefits can not be seen by employing this package to simulate the Collie pools.

### 3.4 LAK2 package

Council (1999) developed a lake package (LAK2) for MODFLOW. Briefly, this package expands the capacities of RES1 package. Iterative loops are provided in this package to calculate and update the stage elevation. Similar to RES1 package, the lake is preferably represented by many cells. Surface water balance calculation is performed for each modeled lake by taking into account the inflow from upstream stream reaches and outflow to the downstream reaches. In order to do so, LAK2 communicates with the Stream Package (Section 3.2). However, leakage is still allowed to occur from the lake even if there is no stream inflow because water balance is performed for each individual lake. All data input for Stream Package and RES1 Package are needed for LAK2 Package. Mathematical formulations of leakage calculation are the same as those in River Package (section 3.1). There will be at least one lake cell remaining active even if the lake has actually gone dry. This allows the lake to be reformed when the watertable rises. LAK2 can increase the instability of a MODFLOW model because of the iterative calculation of stage change for each time step (Council, 1999).

## 4. Recommendations

LAK2 appears to be the most capable package available for simulating groundwater-surface water interactions. This package, however, may produce sensible results only when appropriate data are available and the size of the surface water body is much larger than the individual model cells representing it. Considering the limited data availability for the Collie South Branch, it is not considered appropriate to use this package at this stage. The application of this package in the model will increase model uncertainties, and subsequently uncertainties in model predictions. At a later stage when more data become available, this package may be considered appropriate.

At this stage, it is recommended that the River Package (Section 3.1) be used. The input data required by this package (riverbed elevation, conductance and stage range) are

currently available. The determination of the time-dependent stage change subject to leakage can be done outside the MODFLOW model. This is demonstrated in Section 5.

## 5. Methodology of using River Package to simulate Collie Pools

As described previously, the pools are assumed to be initially in contact with the groundwater system. Mining activities have lowered the watertable, and consequently the pools dry out due to leakage. This drying process can be simulated by the River Package in the following steps:

- a. Set an initial stage in the pool for a transient simulation. This stage represents the starting condition of the pool. Based on this initial stage, the initial volume of water stored in the pool is also known;
- b. Run the model for the period of prediction or calibration;
- c. Plot flow flux of the pool vs simulation time. The flux is positive if water leaks from the pool to the groundwater system;
- d. The flow flux gives information of the accumulated volumetric water leaked from the pool. Based on the known initial water volume stored in the pool, calculate the change of the stage in the pool (the stage should decrease);
- e. Input the calculated time-dependent stage curve into the model, and go to Step (b).

Repeat Steps (b) to (e) to obtain the true stage change curve. When the changes in leakage for two iterations are within a pre-specified criterion, the true solution is obtained as well as the stage change.

The River Package requires that a stage higher than the riverbed elevation must be specified all the time and the river cells cannot be turned off even if the pool has gone dry physically. This problem can be overcome by specifying the stage very close to the riverbed elevation to represent the condition of a dry pool. To enable the pool to dry out completely, the regional watertable has to be lower than the pool bottom elevation. In this case, the leakage from the pool to the groundwater is calculated as:

$$Q = CRIV * (Hs - RBOT)$$

Hs is the stage, RBOT is the pool bottom elevation. If Hs is set very close to RBOT (but larger than RBOT, eg  $Hs = RBOT + 1e-10$ ), Q is close to zero. Under this condition, the pool leakage is zero although the river cells are still active. This is equivalent to the effect of turning off the river cells.

### 5.1 Example 1 - Drying Process

This example shows the modelling results by applying the above steps to simulate the drying process of Long Pool. It should be noted that this is an example only and some values, eg initial water volume in Long Pool, pumping conditions, evaporation rate, are assumed.

### 5.1.1 Initial condition

Long Pool was initially in contact with regional groundwater flow and groundwater discharges to Long Pool. The initial stage in Long Pool was 179 m AHD.

### 5.1.2 Stressed condition

A wellfield is constructed near Long Pool. Significant groundwater is being withdrawn from this wellfield, and this lowers the regional watertable. The watertable near Long Pool is eventually lowered below the pool bottom elevation. Leakage from Long Pool occurs. Since no sufficient rainfall precipitation is available, leakage exceeds the total inflow water to Long Pool and the pool becomes dry.

### 5.1.3 Modelling objectives

The model is expected to show the process of how Long Pool gets dry and how long it takes for the pool to become completely dry subject to the current pumping scenarios.

### 5.1.4 Model construction

A 3D-groundwater flow model is constructed with MODFLOW. The Long Pool is simulated by River Package. The stage is 179 m AHD in Long Pool and is a constant. For this condition, the model shows that Long Pool gains water from the groundwater system at a rate of 300 m<sup>3</sup>/day. Using this solution as the initial condition, a transient model is constructed by including the pumping conditions.

### 5.1.5 Modelling results and water balance calculation for Long Pool

The stage in the pool is a time-dependent parameter and is to be determined. The leakage from the pool is dependent on the stage and the groundwater condition. Therefore, the stage and the leakage are coupled and iterations are needed to obtain the true solution.

A constant stage of 179 m is first used in the transient model and this is shown as 'initial guess' curve in Figure A. After running the model, the flux (water exchange through the pool) is obtained from the model as 'Iteration\_1' shown in Figure B. It can be seen that flux becomes positive at about 40 days, which implies that leakage from the pool occurs at 40 days. This flux increases with the simulation time as the watertable continuously drops down. The flux reaches a maximum value at 90 days and then remains constant. This means that at 90 days, the watertable has dropped down below the pool bottom elevation. Leakage from the pool is dependent on the depth of water in the pool and independent of the regional watertable (see formula in section 5). Since the stage is constant in the pool, the leakage is constant too.

A water balance calculation is then performed for the Long Pool. The shape of the pool is assumed to be rectangular with a length of 320 m and a width of 15.9 m. This gives a water surface area of 5 087 m<sup>2</sup>. With an initial stage of 179 m AHD, the initial water volume in the pool is about 10 174 m<sup>3</sup> (pool bottom elevation is 177 m AHD, water depth is 2 m in the pool). An evaporation rate of 4.1 mm/day (~1500 mm/year) applies to Long

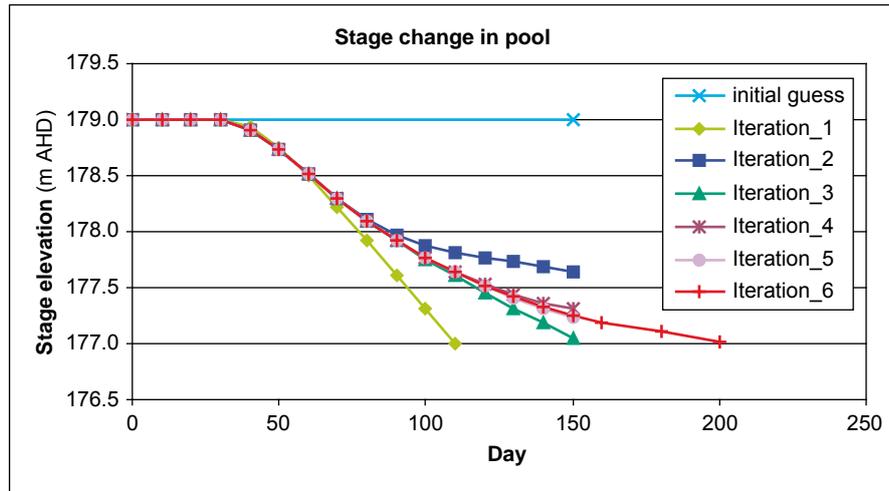


Figure A. Stage change in pool

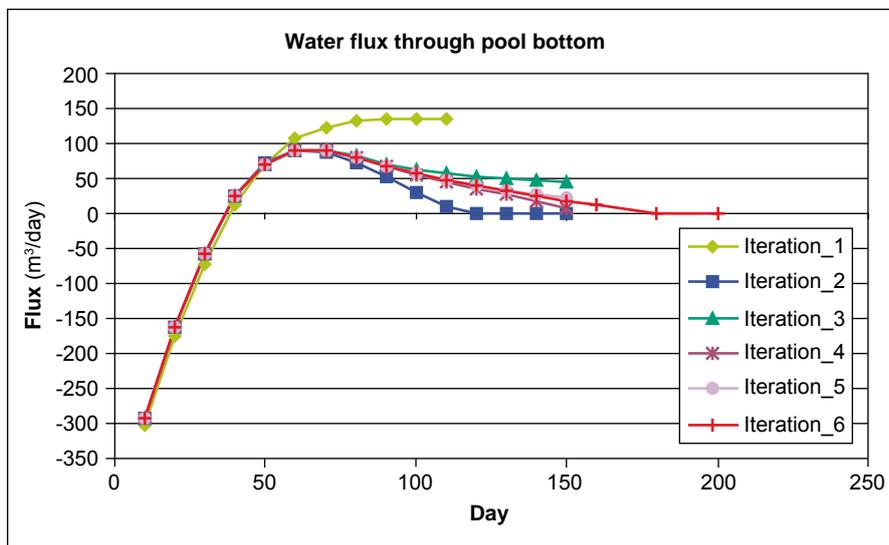


Figure B. Water flux through pool bottom

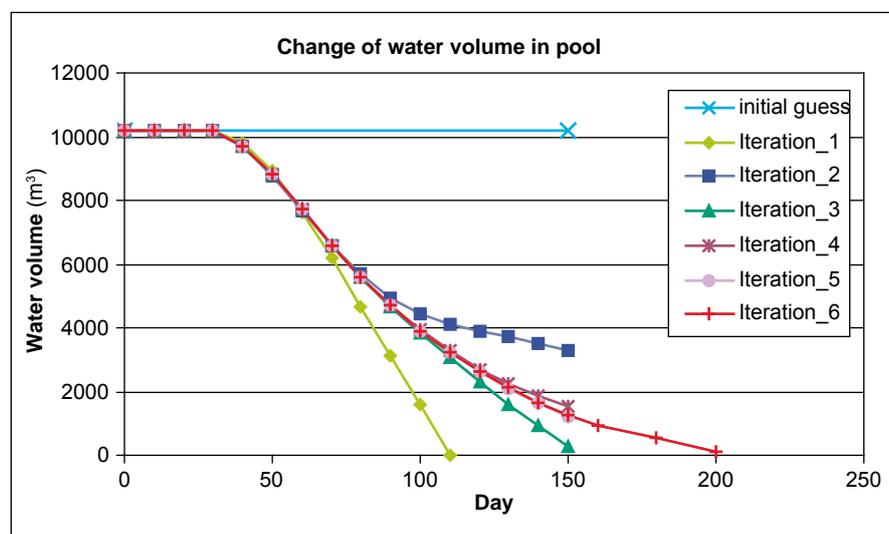


Figure C. Change of water volume in pool

Pool. Based on the evaporation rate and the flux, the remaining volume of water in the pool can be calculated and shown as 'Iteration\_1' in Figure C. The corresponding stage change is shown as 'Iteration\_1' in Figure A. The curve 'Iteration\_1' in Figure C shows that the pool becomes dry at 110 days. However, this must have been underestimated since the leakage has been overestimated from a constant stage, which actually should decrease.

The transient stage height from 'Iteration\_1' is input to the model and the model is run for the second iteration. Flux of 'Iteration\_2' can be plotted as in Figure B. The water balance calculation is repeated and water volumes are plotted as 'Iteration\_2' in Figure C and the stage change as 'Iteration\_2' in Figure A. It is found that at the 6th iteration, the flux matches with that of the 5th iteration as shown in Figure B, and hence the true solution has been obtained at the 6th iteration. The true stage change solution is also calculated as 'Iteration\_6' in Figure A. The pool gets completely dry at about 200 days.

## 5.2 Example 2 - Wetting Process

This wetting process of Long Pool is designed as the reverse process of the drying as shown in Example 1. In this example, the pumping conditions are turned off, and the watertable should recover to the initial condition of Example 1.

The iteration procedure is basically similar to those in Example 1. The Long Pool is initially dry and the initial stage in the pool is assumed as the pool bottom elevation (177 m AHD, Fig. D). When the watertable rises above the pool bottom elevation, groundwater discharges to the pool and the pool gets wet.

Figures D, E and F show the iterative procedure. It is assumed that when the stage rises to an elevation of 179 m AHD, the pool is full and the stage will not rise any more. If groundwater continues to recharge the pool, the volume of water from groundwater recharge will become streamflow, not accumulated in the pool. It can be seen that the true solution is obtained at the 4th iteration. Groundwater starts recharging the pool at 30 days after turning off the pumping wells. The pool is full after 150 days. It is noted that in this example, evaporation in the pool is not considered in water balance calculation for simplification. If evaporation was considered, it would take longer for the pool to fill.

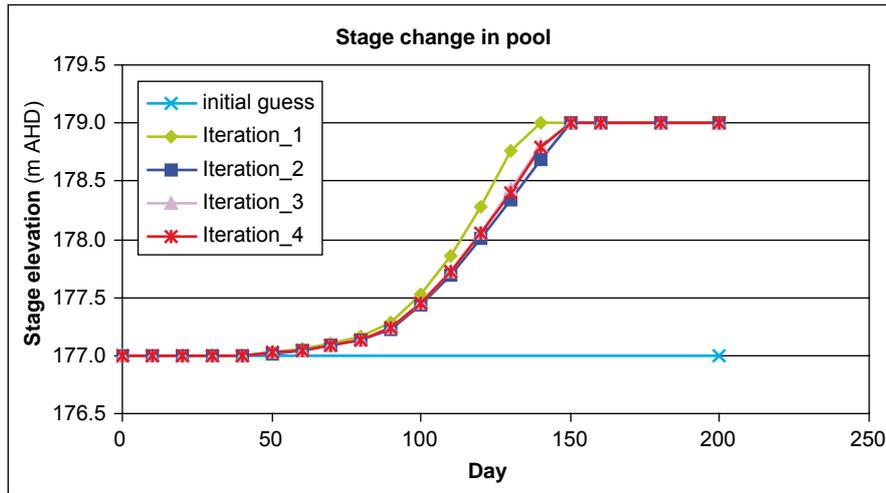


Figure D. Stage change in pool

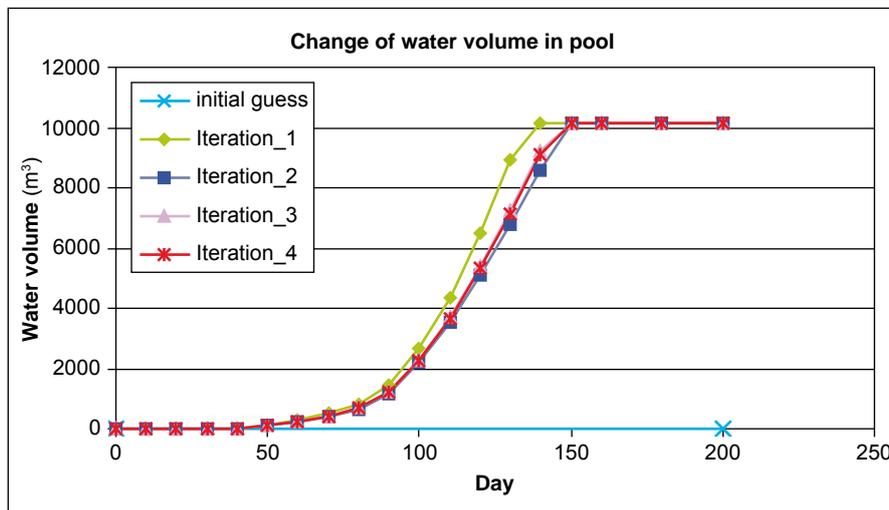


Figure E. Change of water volume in pool

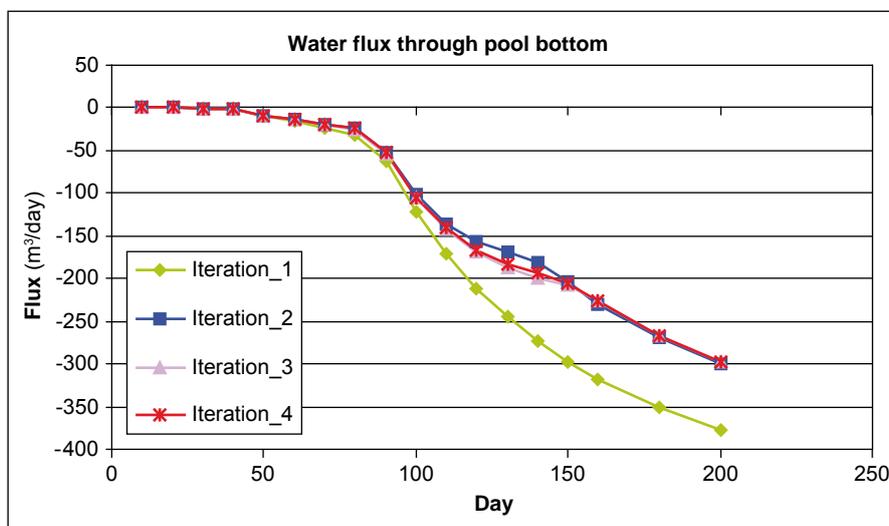


Figure F. Water flux through pool bottom

## 6. Discussion

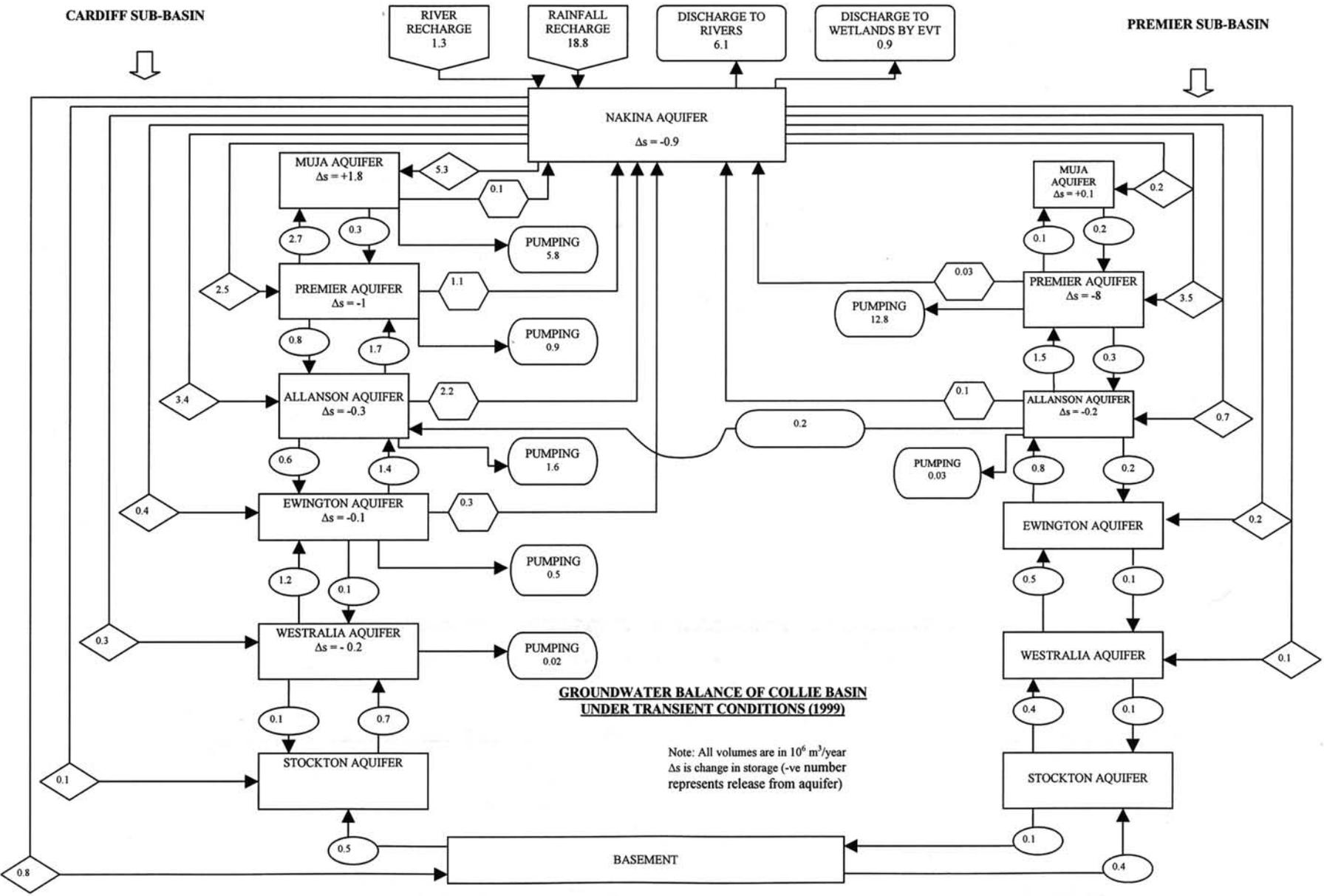
The above examples show that the solution of the stage change in pools is achievable using the River Package by performing water balance for the pool outside the model. One of the factors that affect the accuracy of this approach is the time step size. In this example, a time step size of 5 days is used. However, a time step size of 10 days does not generate noticeably different results.

The water balance calculation approach outlined above is convenient, and is considered appropriate to the data availability at this stage. Whilst other available packages may offer automated water balance calculation within the model, the data to support these packages are currently unavailable. If data become available in the future, conversion to these packages could be undertaken. In the meantime, it is considered that the approach outlined above will generate the required results using currently available data.

## 7. References

- Council, G.W., 1999, A Lake Package for MODFLOW (LAK2), Documentation and User's Manual, version 2.2, HSI GEOTRANS.
- Fenske, J.P., Leake, S.A., and Prudic, D.E., 1996, Documentation of a computer program (RES1) to Simulate Leakage from Reservoirs using the Modular Finite-difference Groundwater Flow Model (MODFLOW), US Geological Survey, open-file report 96-364.
- McDonald, M.G. and Harbaugh, A.W., 1988, A Modular Three-dimensional Finite-difference Groundwater Flow Model, US Geological Survey Techniques of Water-Resources Investigations, Book 6, chap. A1.
- Prudic, D.E., 1989, Documentation of a Computer Program to Simulate Stream-Aquifer Relations using a Modular, Finite-difference, Groundwater Flow Model, US Geological Survey, open-file report 88-729.

# Appendix B - Water balance of the Collie Basin



# Appendix C - Contours of surfaces and isopachs of the Collie Basin strata

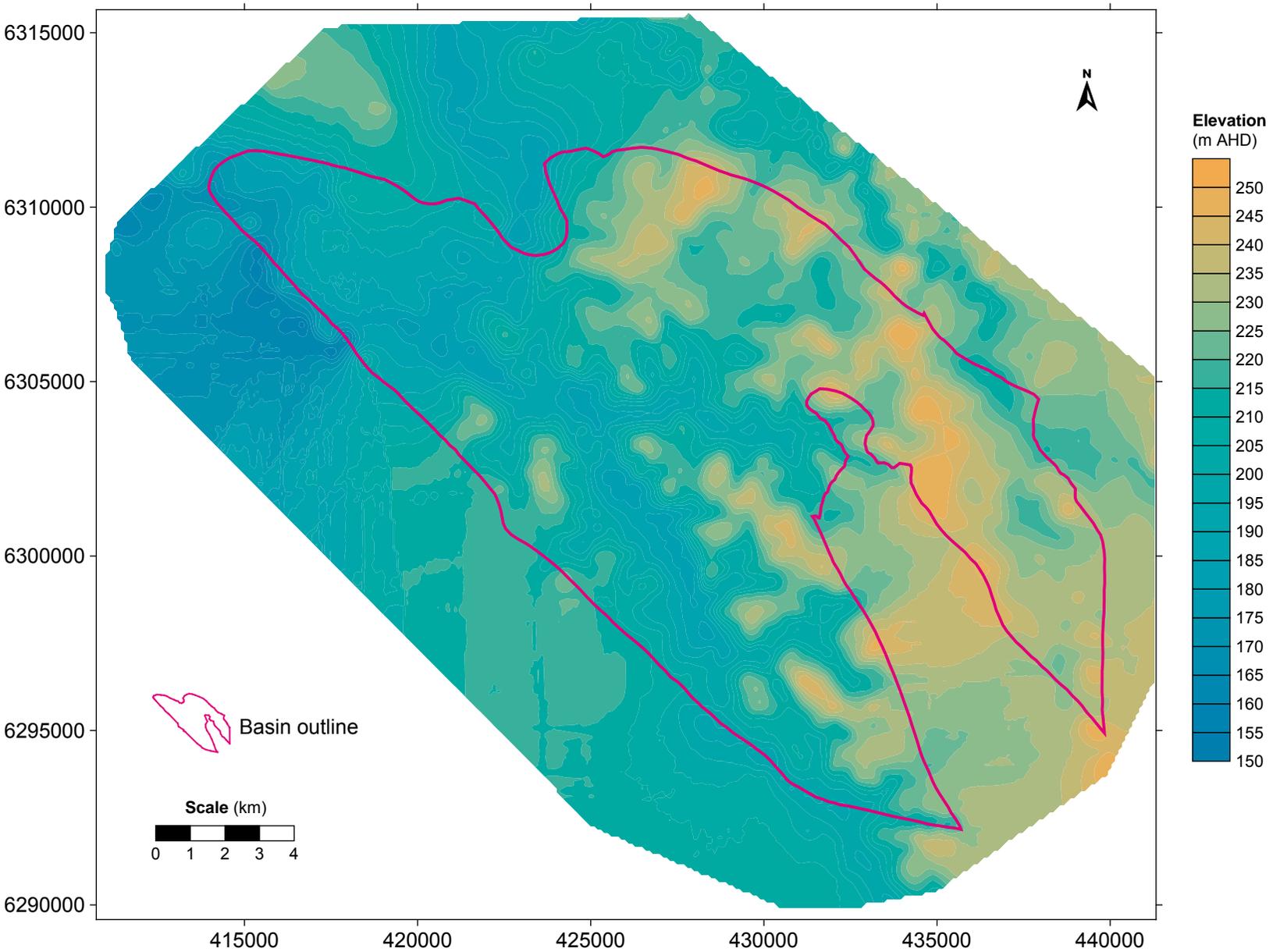


Plate 1. Elevation of Ground Surface in the Model

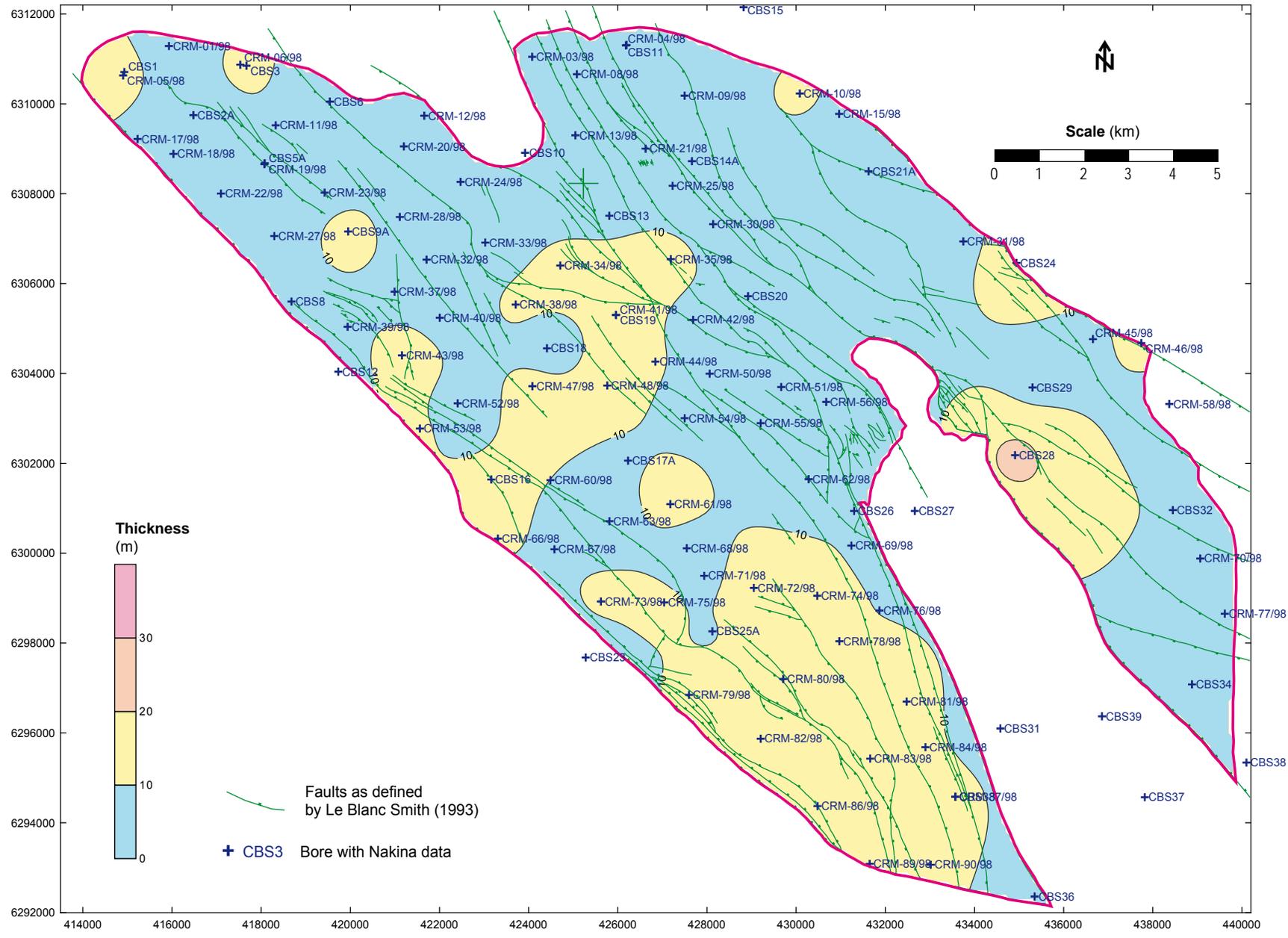


Plate 2. Nakina-Cainozoic Thickness

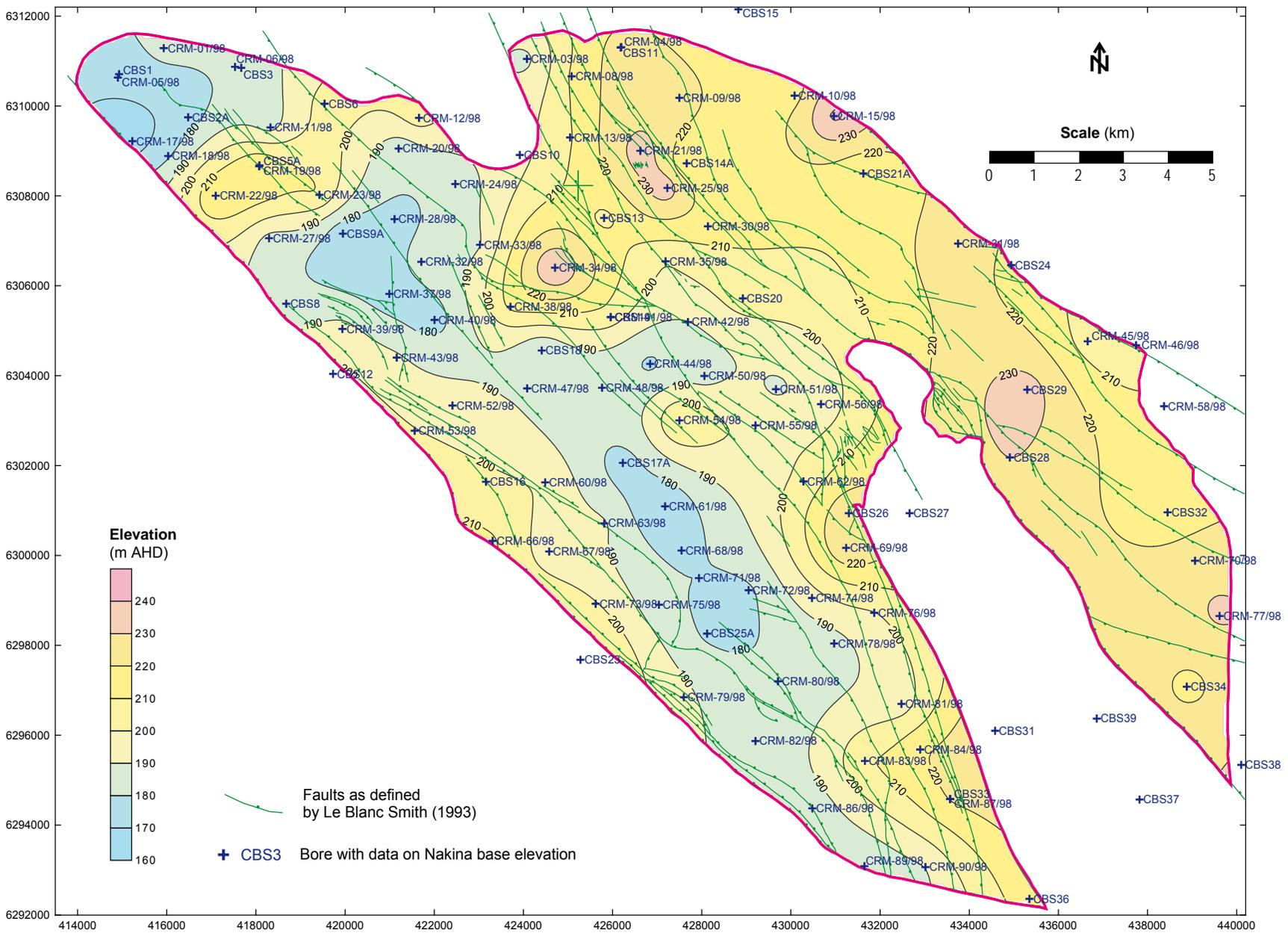


Plate 3. Nakina Base Elevation

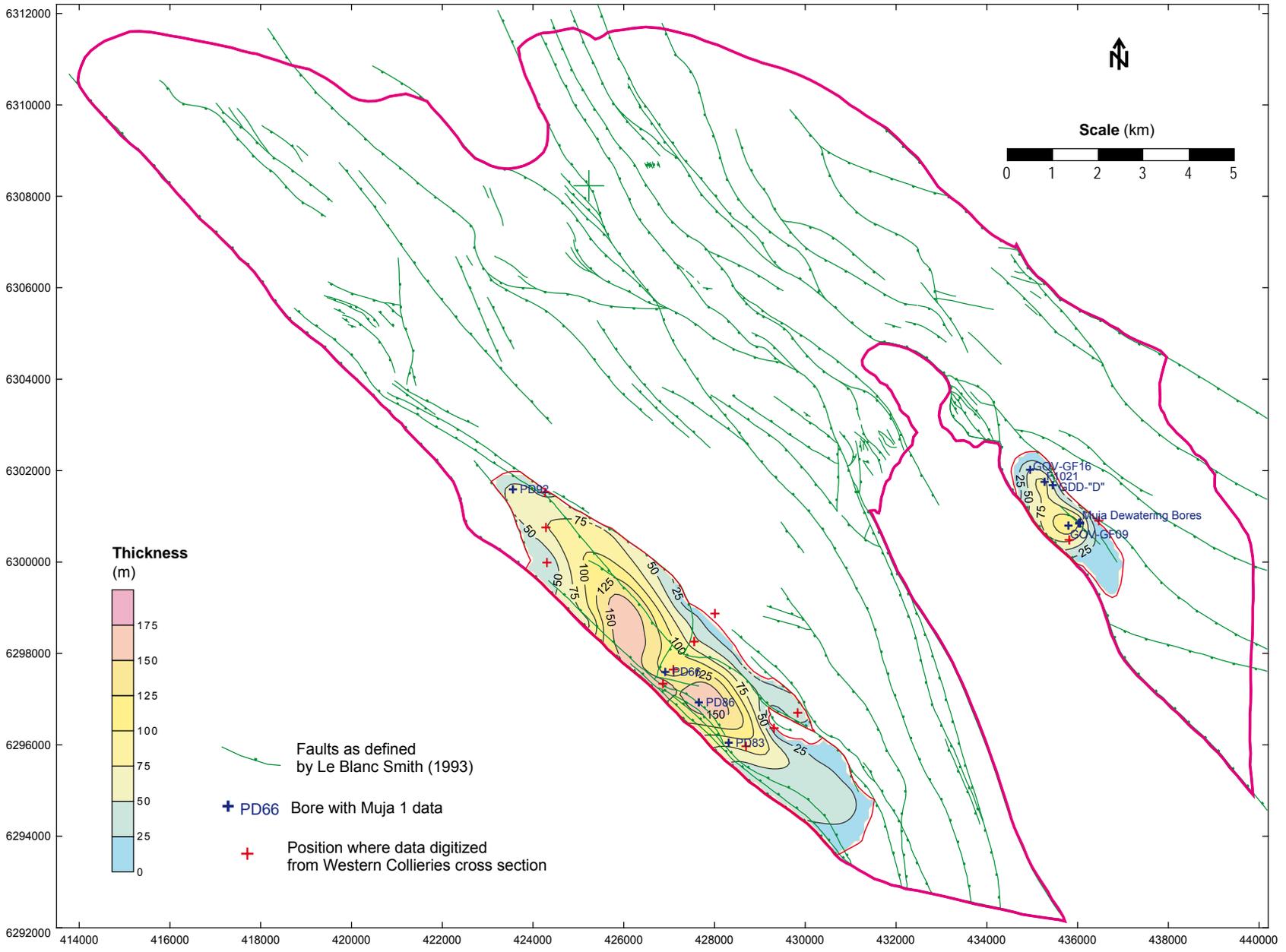


Plate 4. Muja 1 Thickness

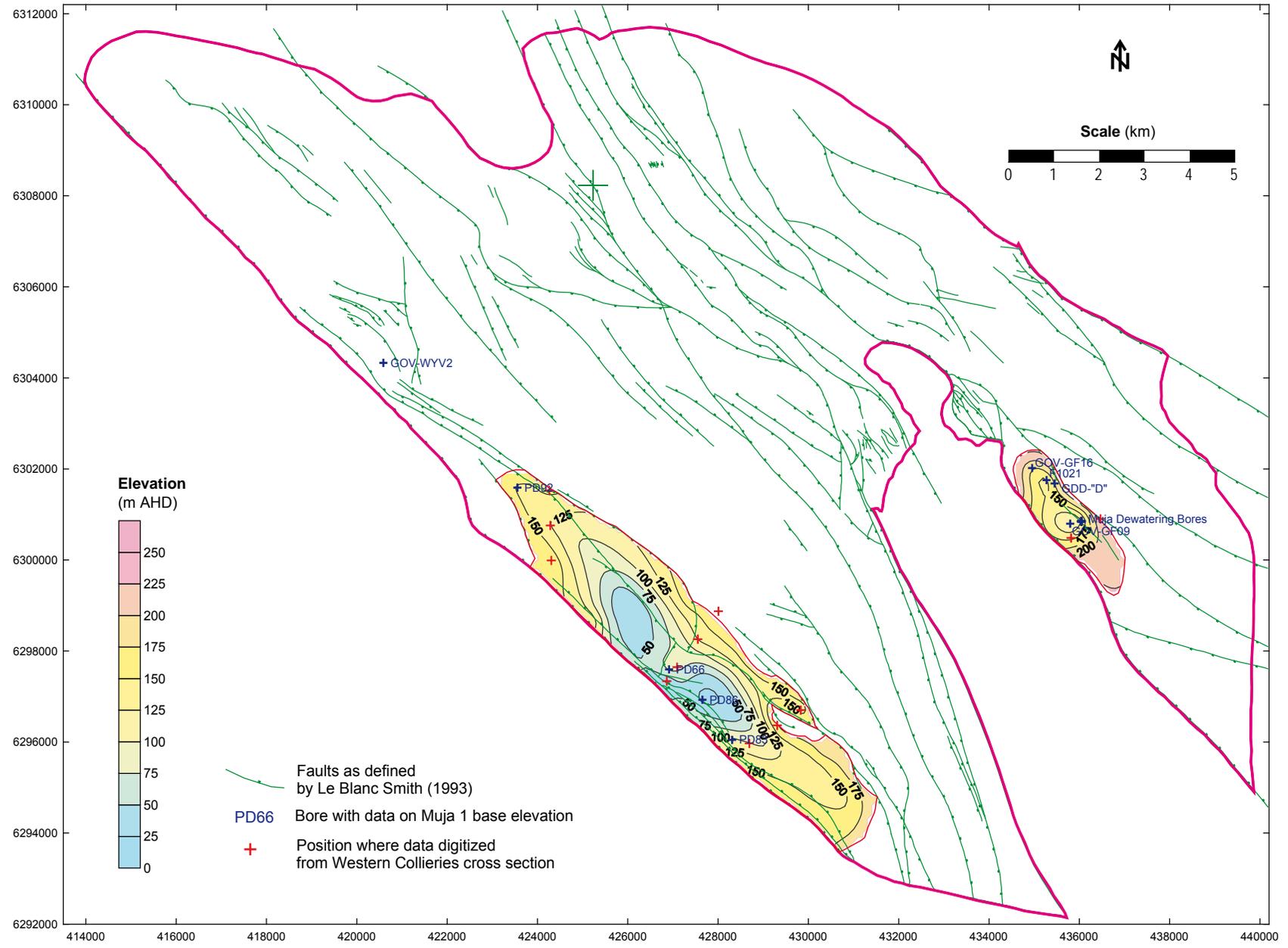


Plate 5. Muja 1 Base Elevation

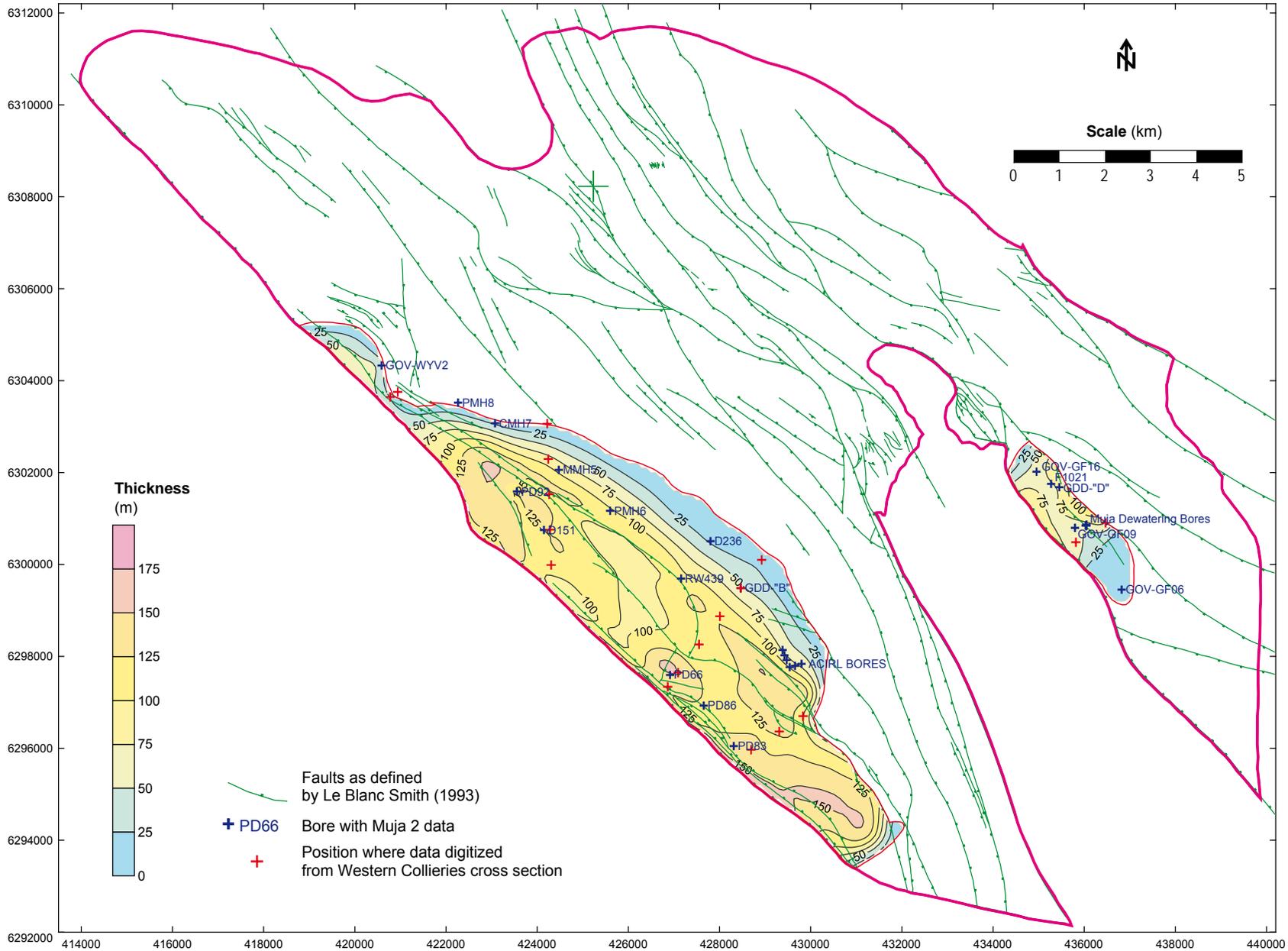


Plate 6. Muja 2 Thickness

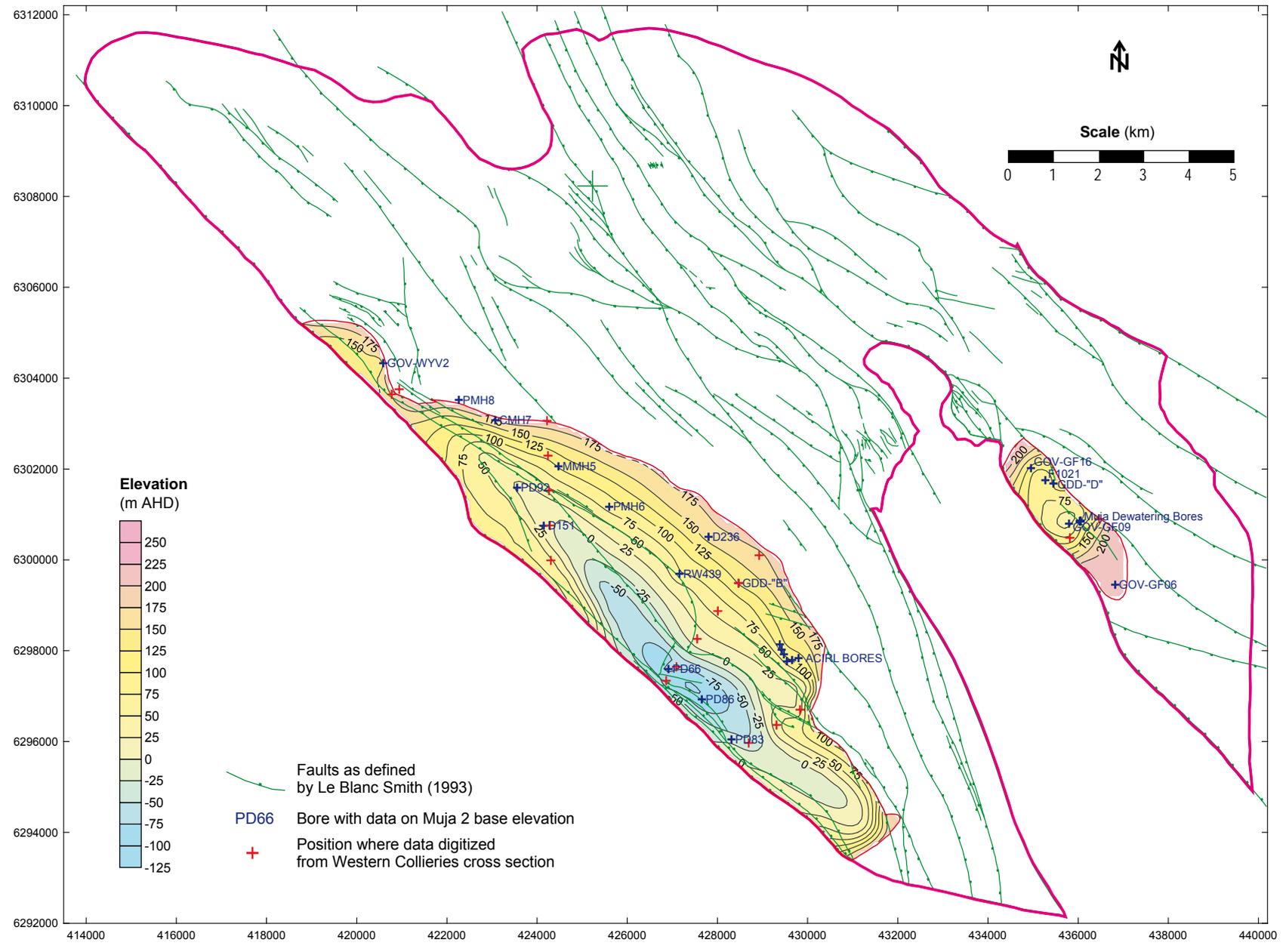


Plate 7. Muja 2 Base Elevation

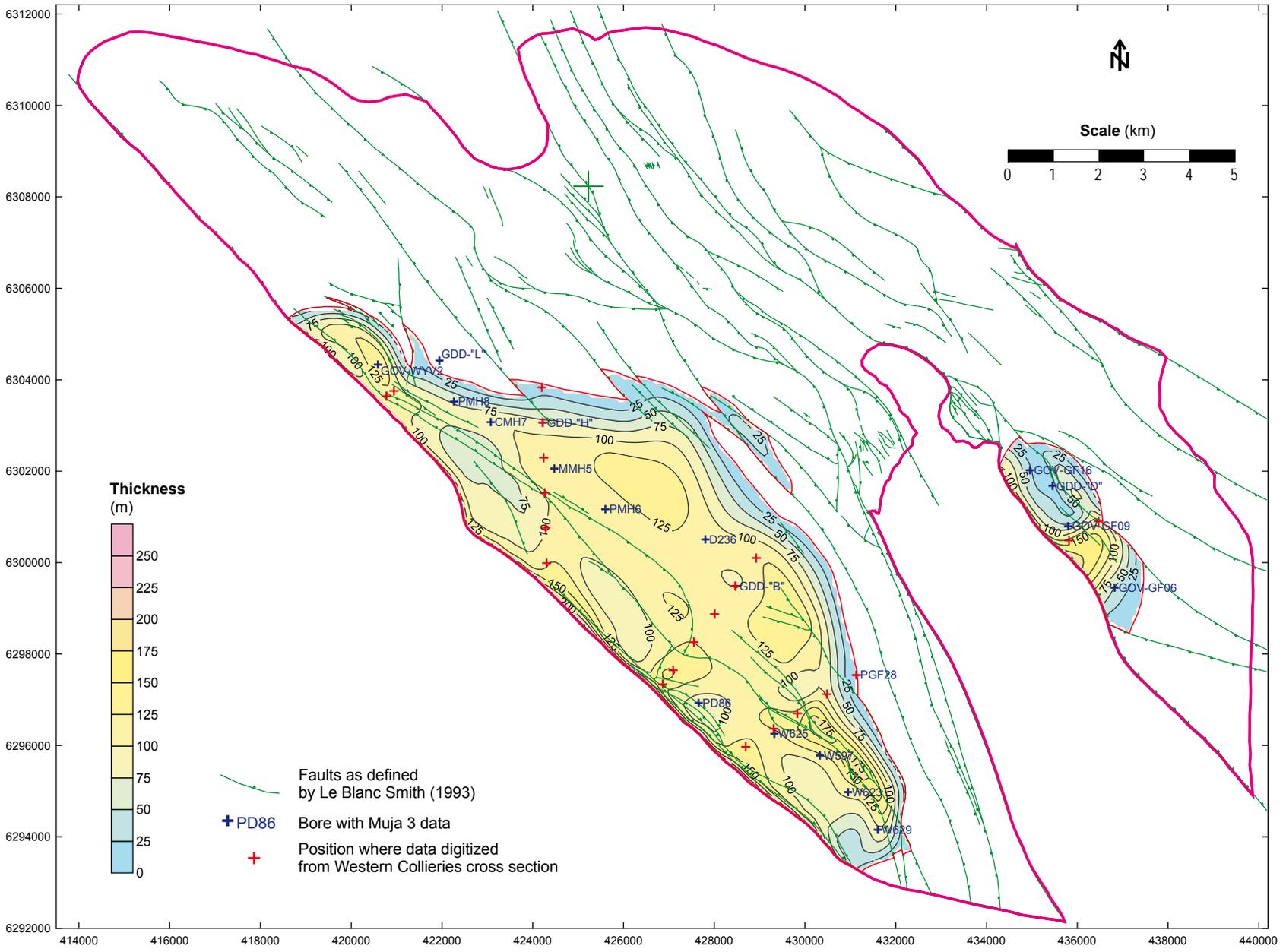


Plate 8. Muja 3 Thickness

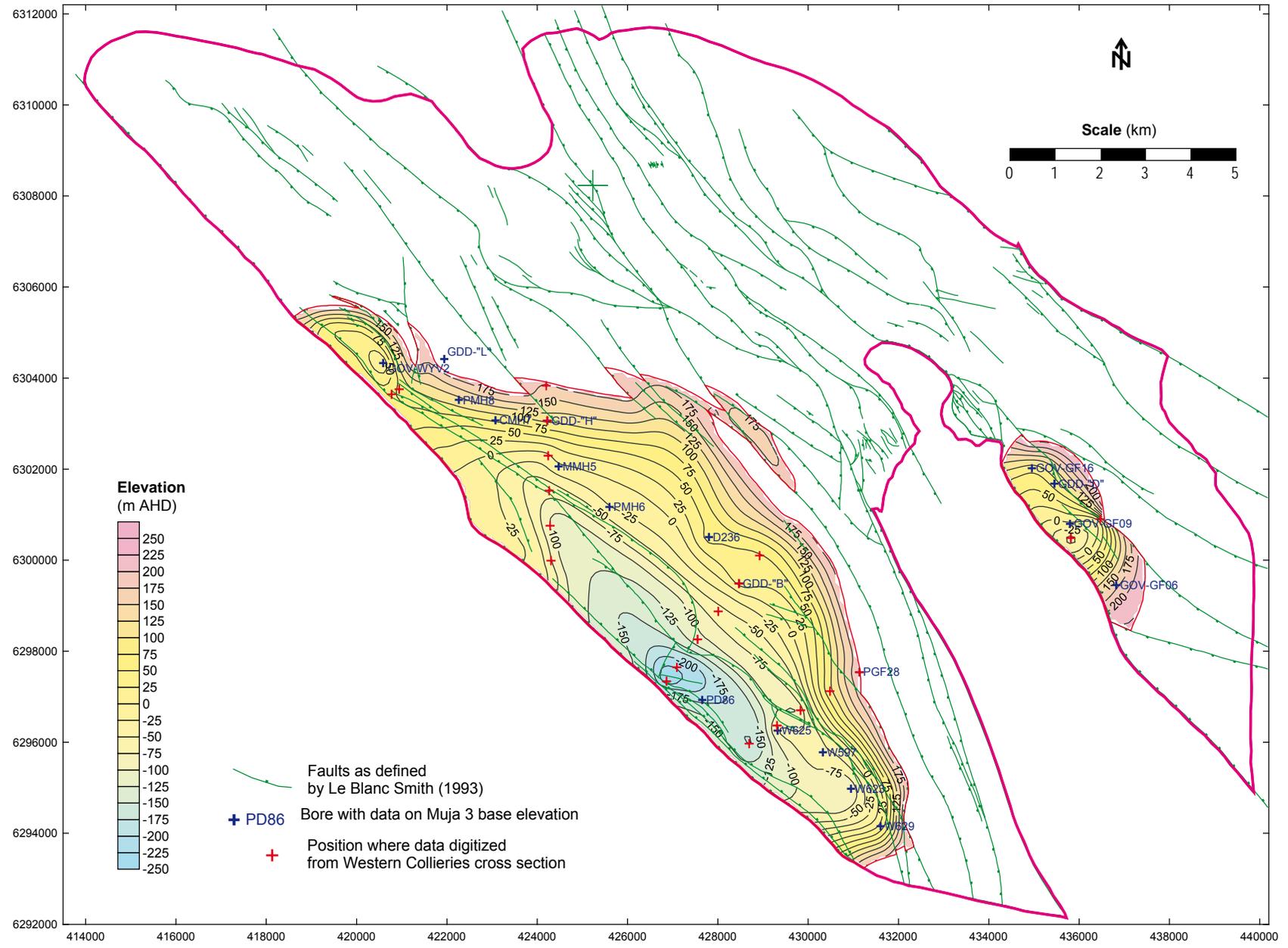
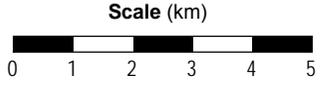


Plate 9. Muja 3 Base Elevation

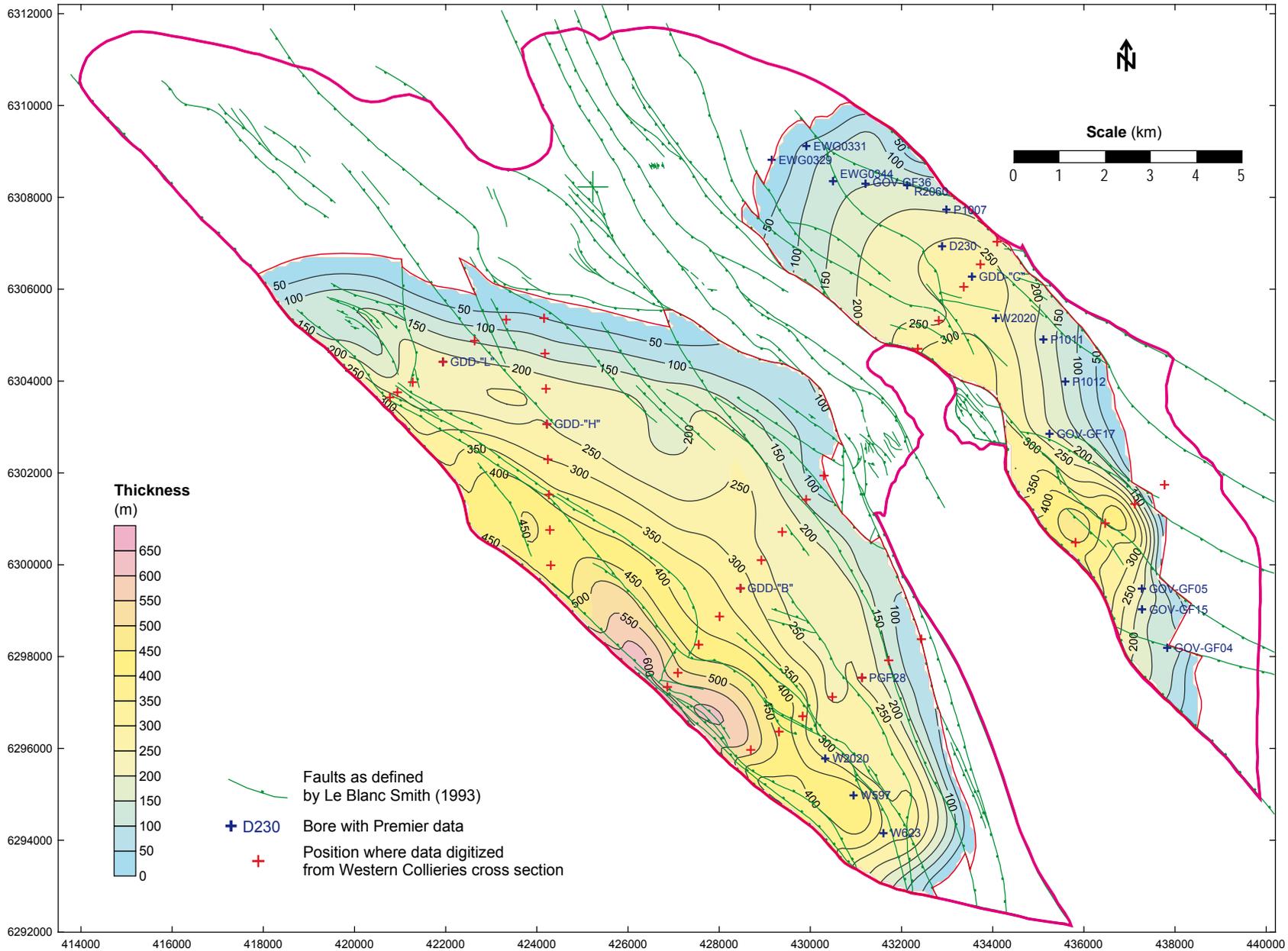


Plate 10. Premier Thickness

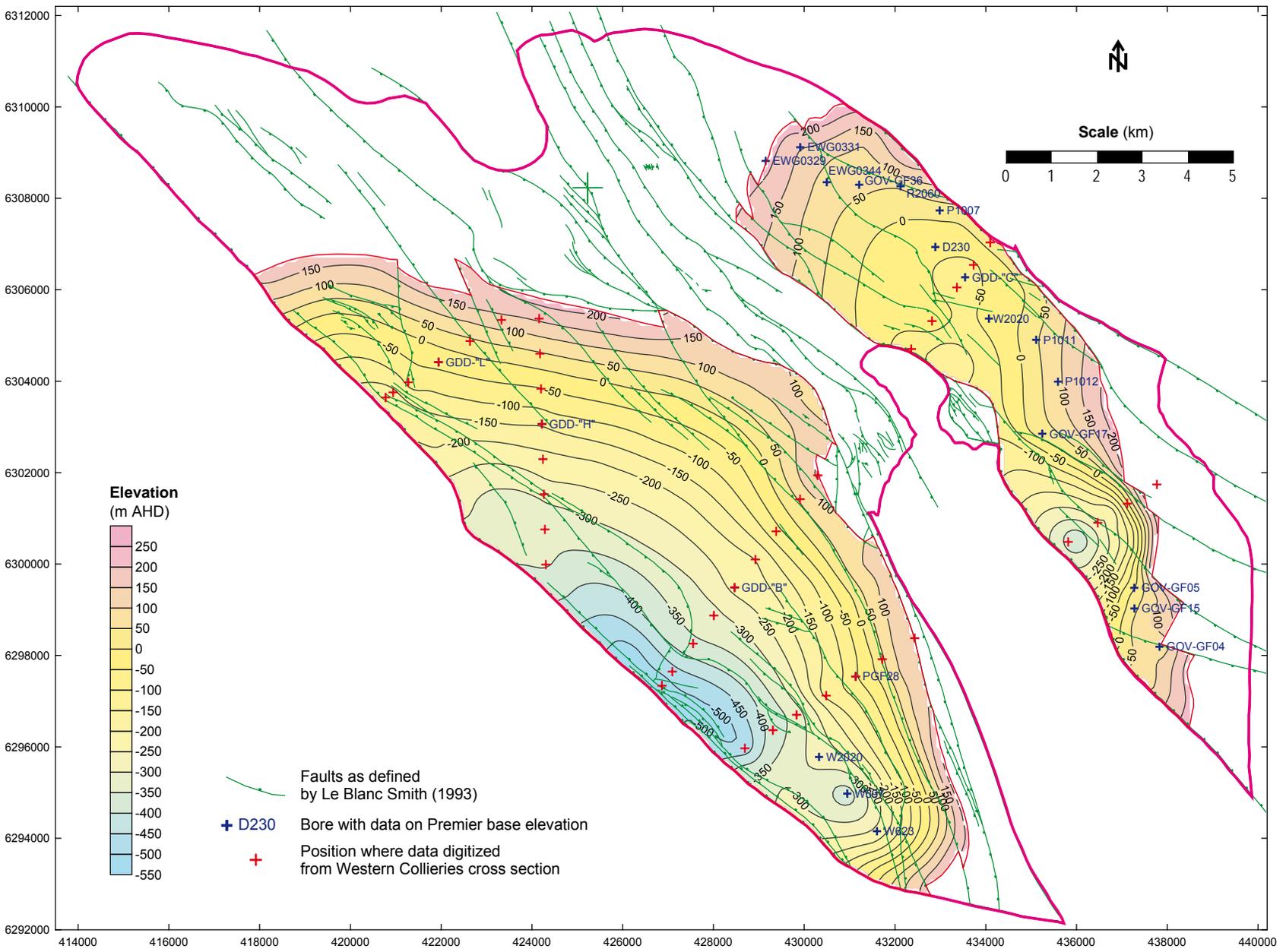


Plate 11. Premier Base Elevation

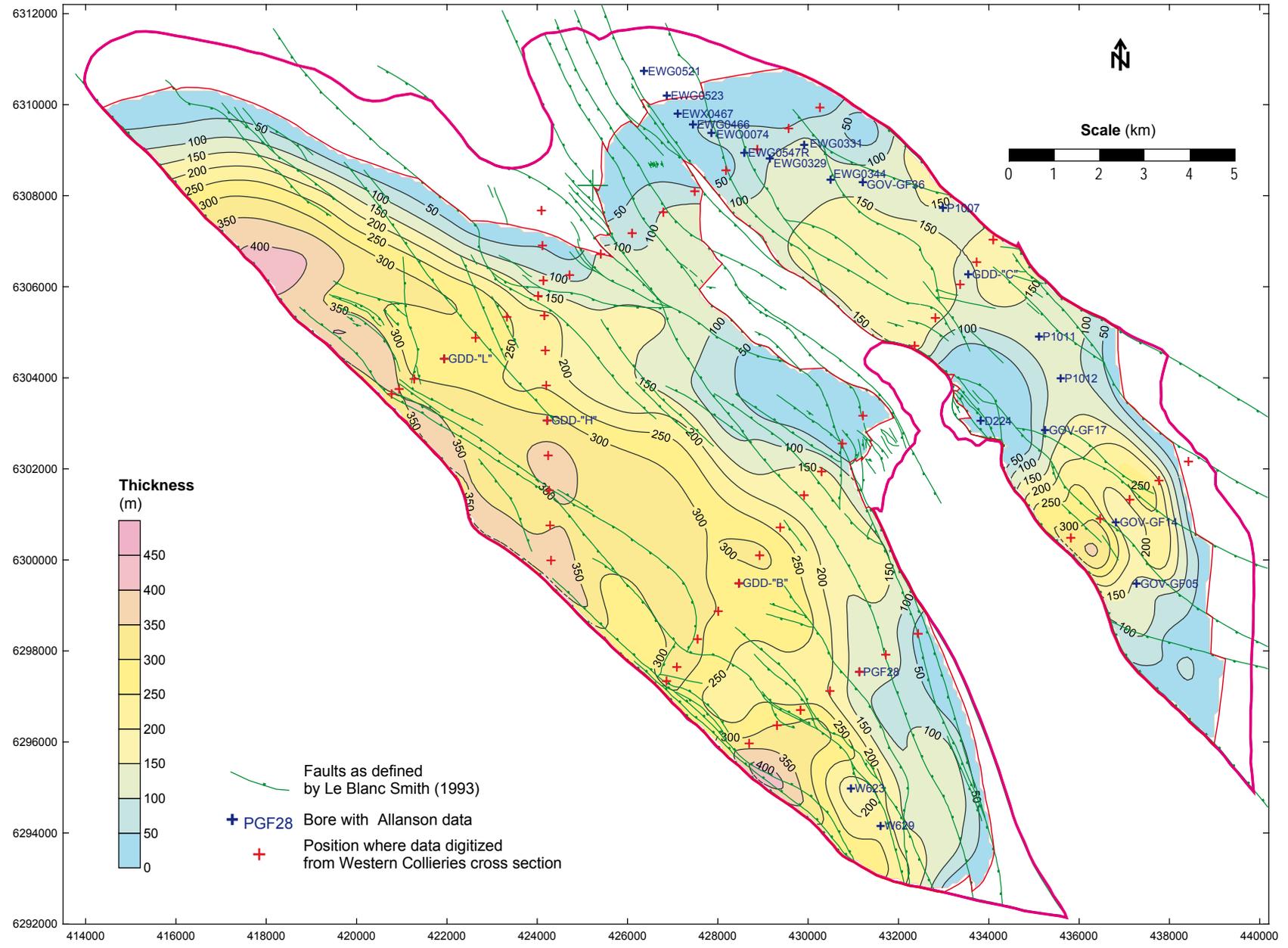


Plate 12. Allanson Thickness

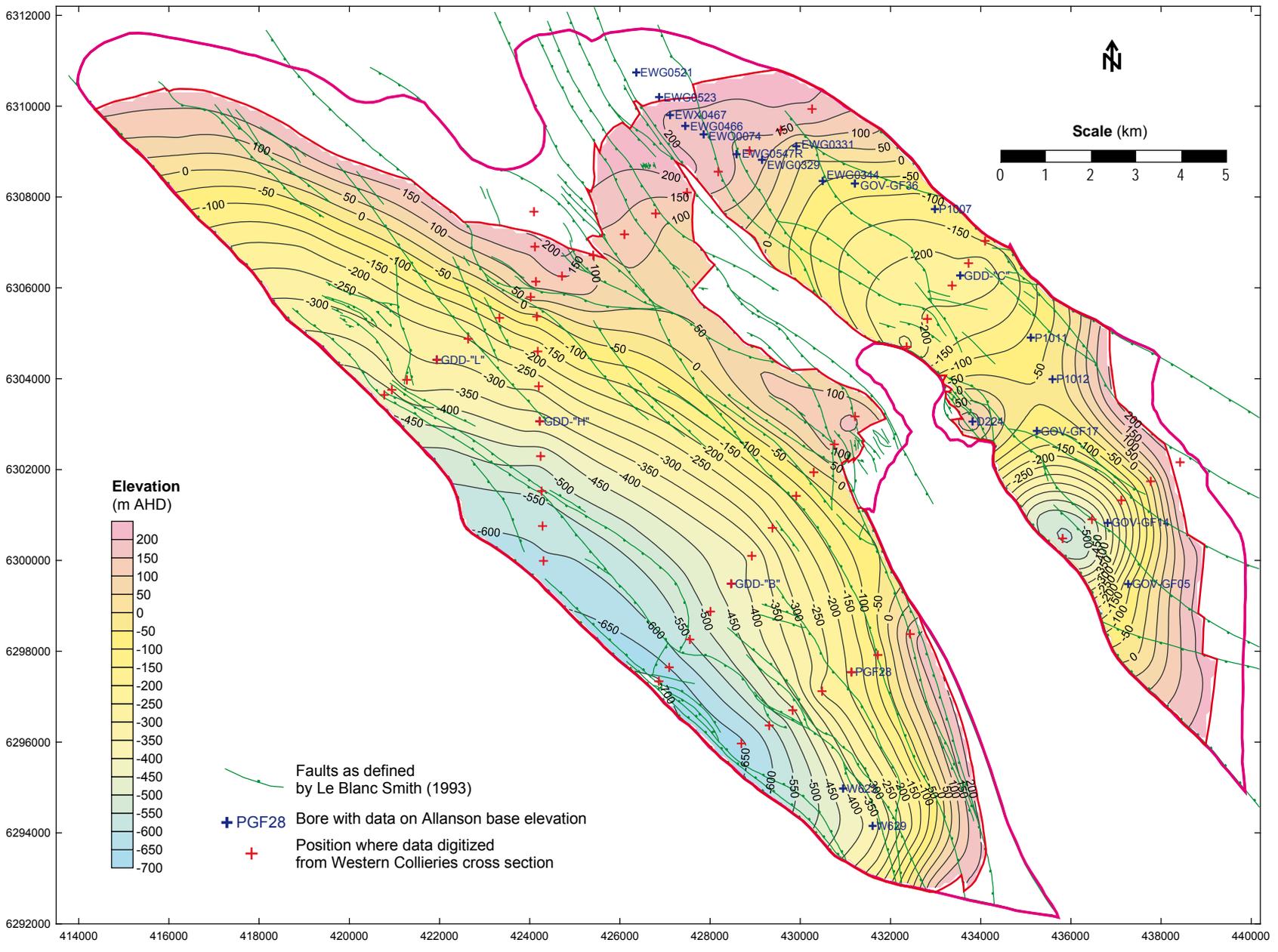


Plate 13. Allanson Base Elevation

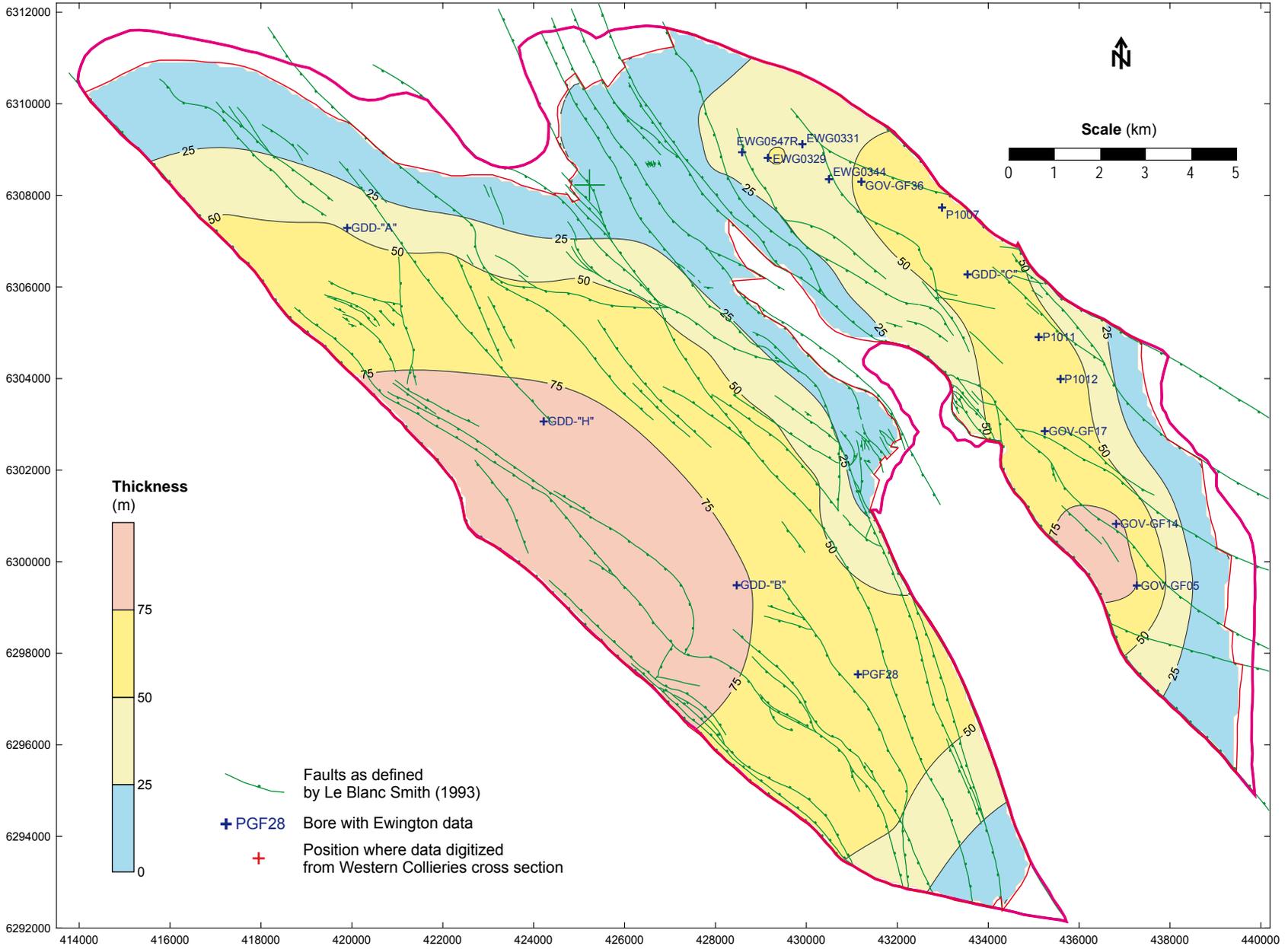


Plate 14. Ewington Thickness

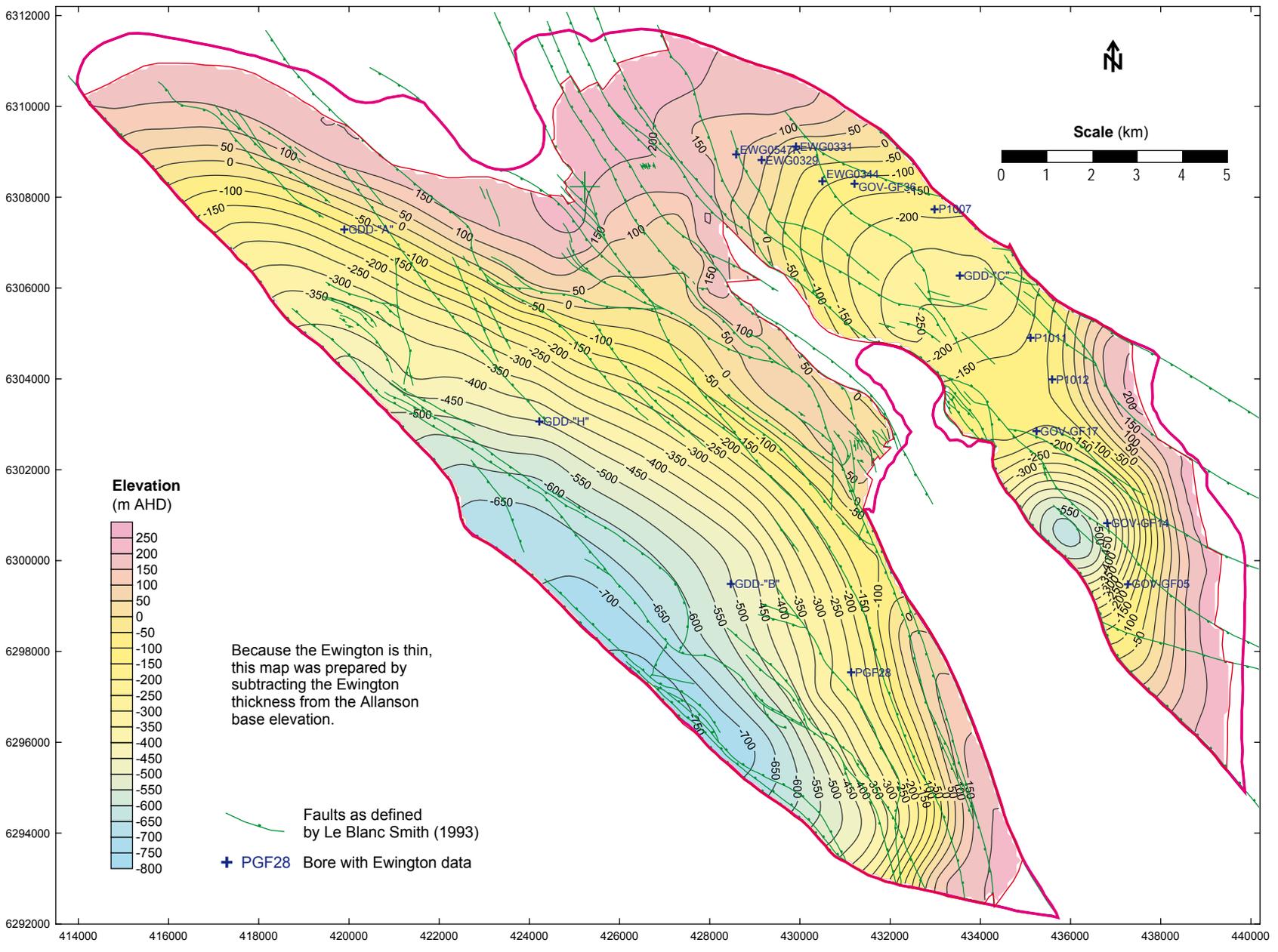
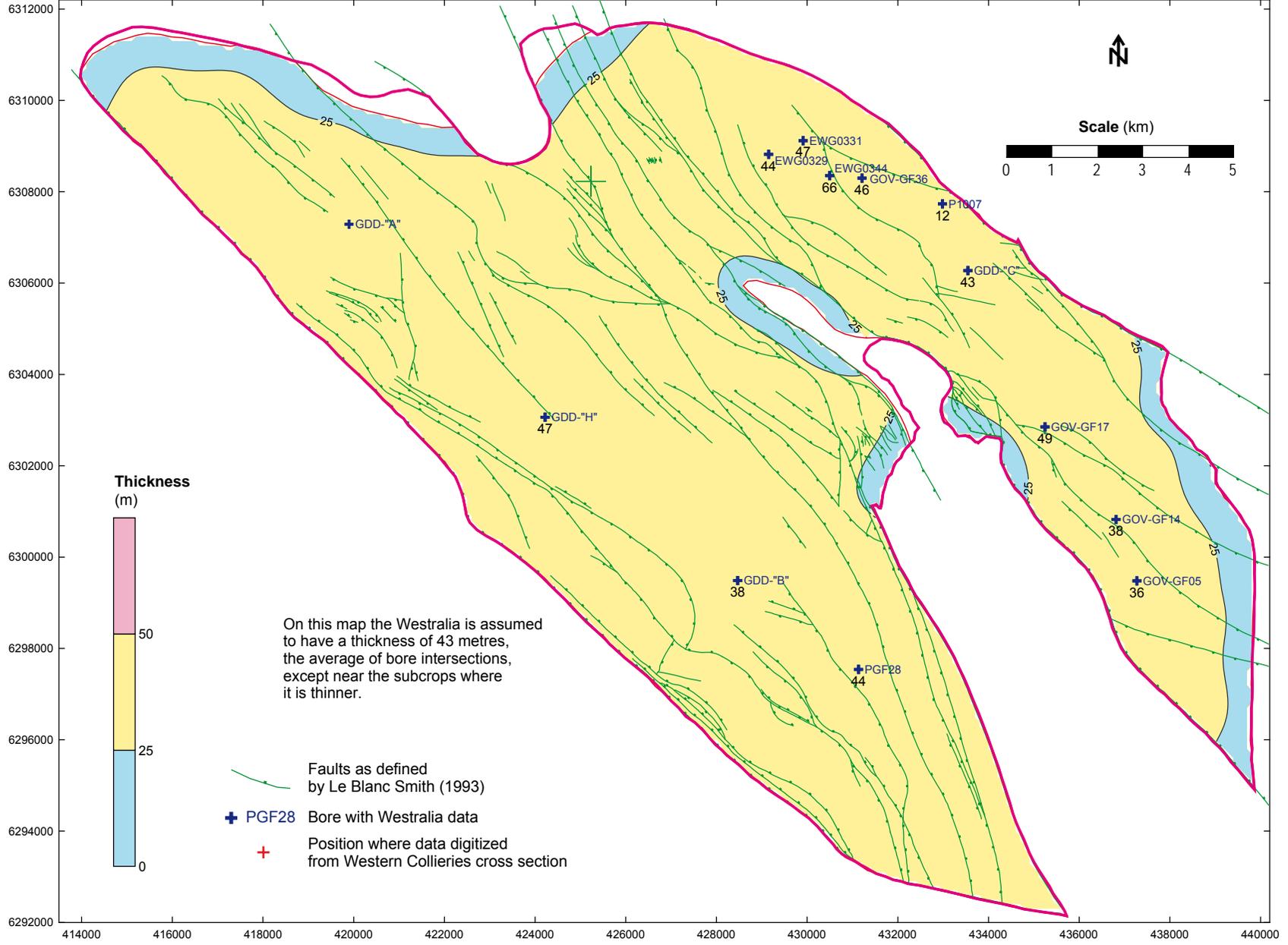


Plate 15. Ewington Base Elevation

Plate 16. Westralia Thickness



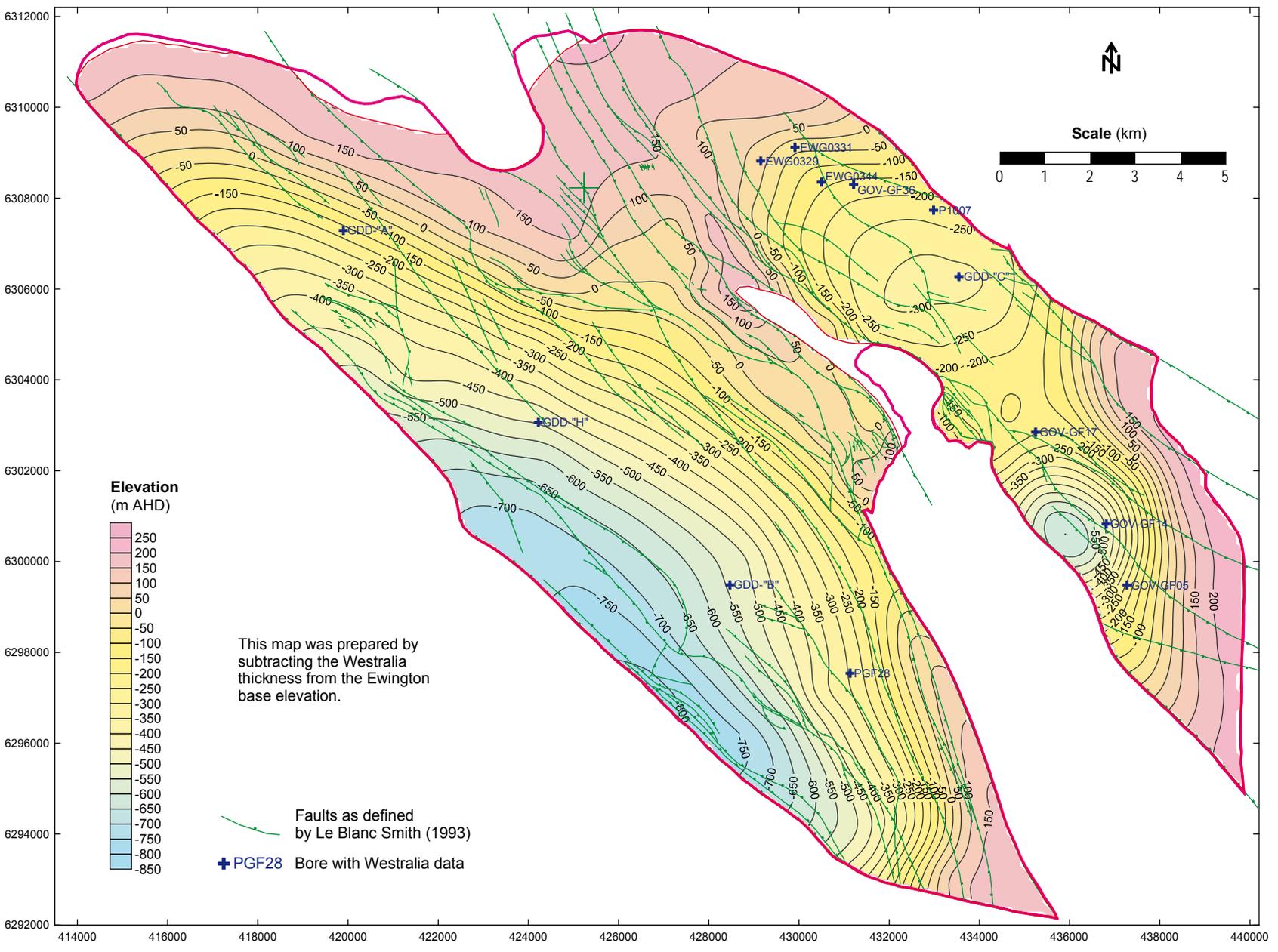


Plate 17. Westralia Base Elevation

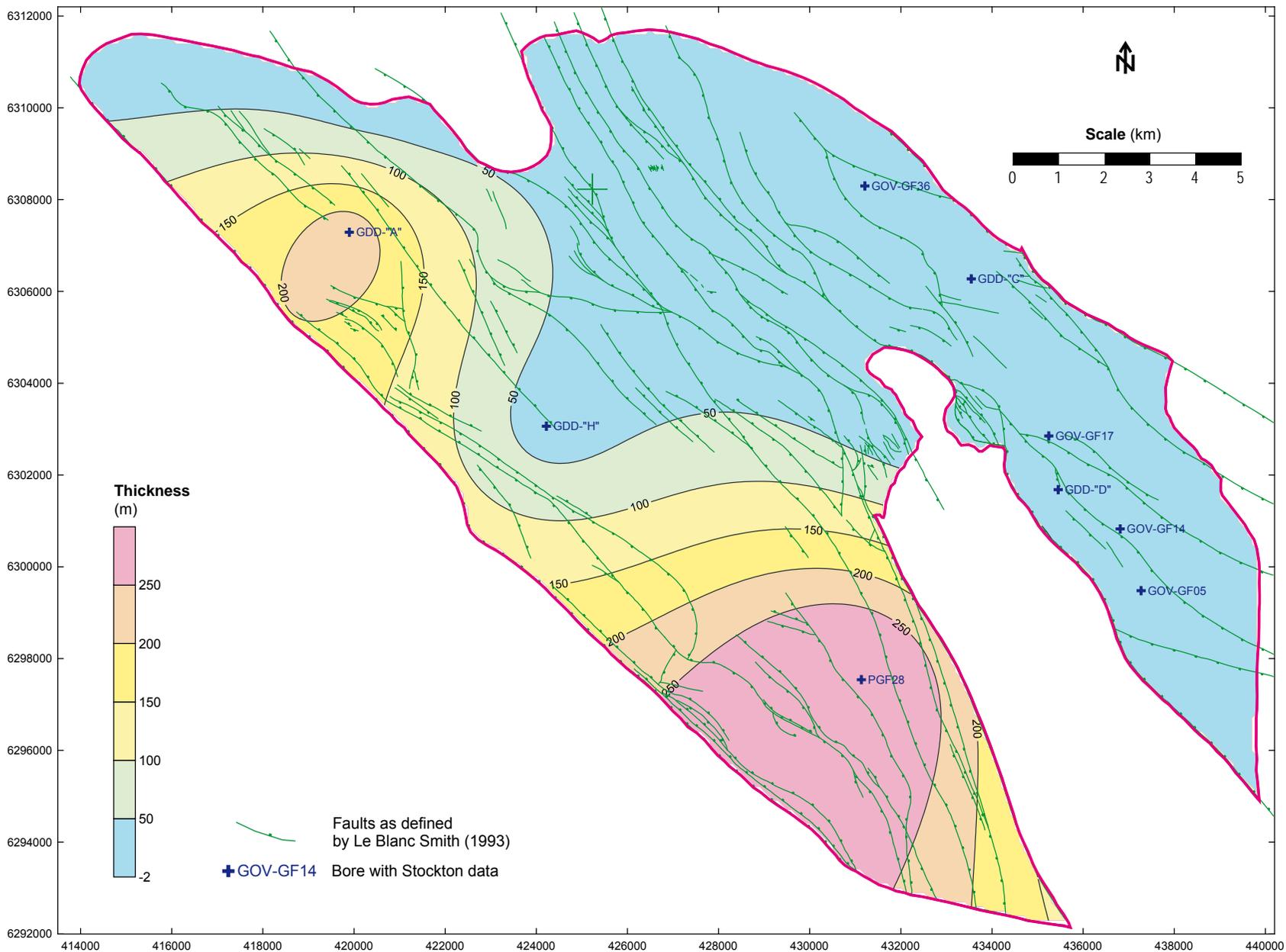
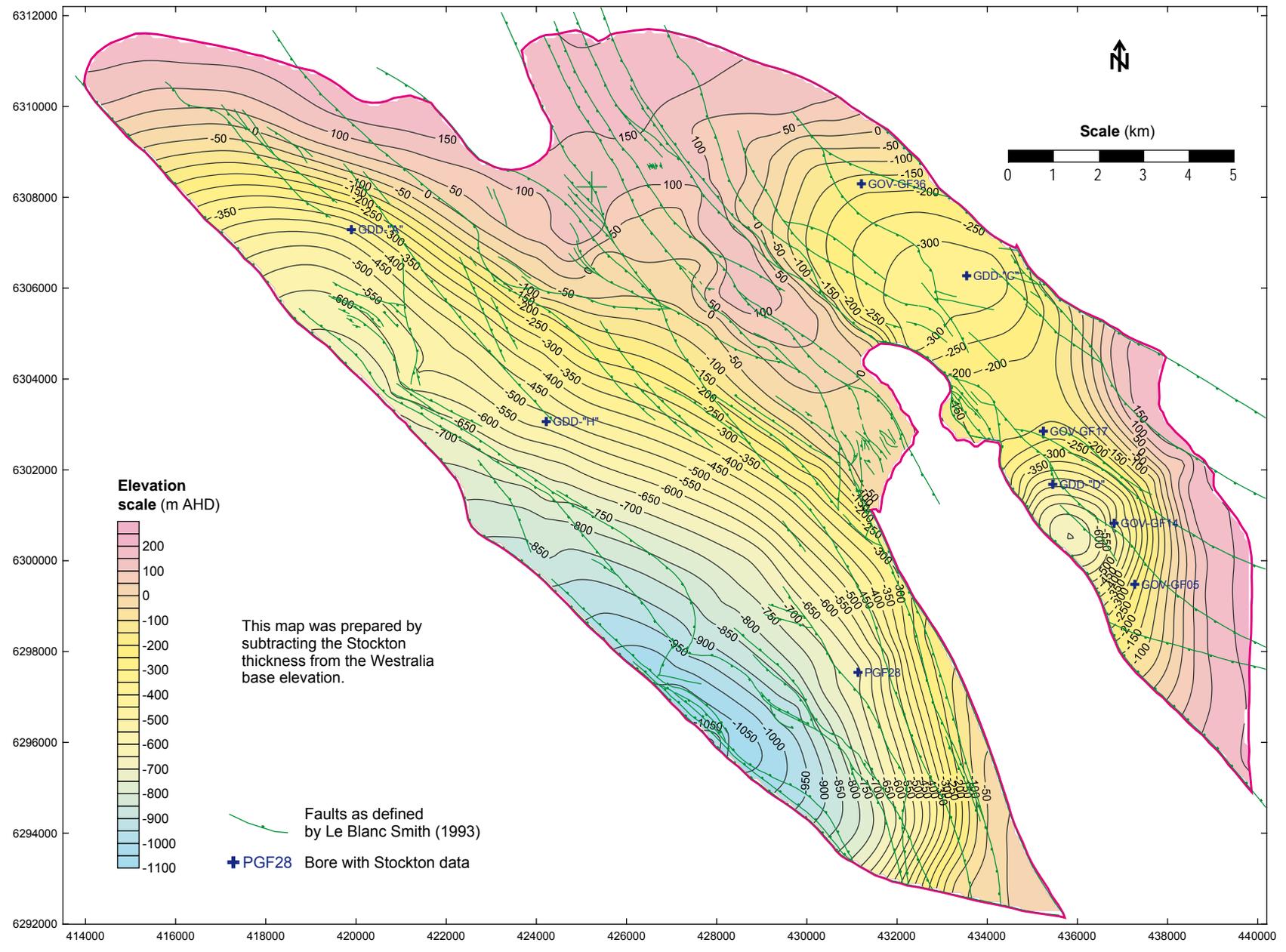


Plate 18. Stockton Thickness



This map was prepared by subtracting the Stockton thickness from the Westralia base elevation.

Faults as defined by Le Blanc Smith (1993)  
 + PGF28 Bore with Stockton data

**Elevation scale (m AHD)**

200  
100  
0  
-100  
-200  
-300  
-400  
-500  
-600  
-700  
-800  
-900  
-1000  
-1100

Plate 19. Stockton Base Elevation (Top of Archaean)

# Appendix D - Potentiometric heads in model layers

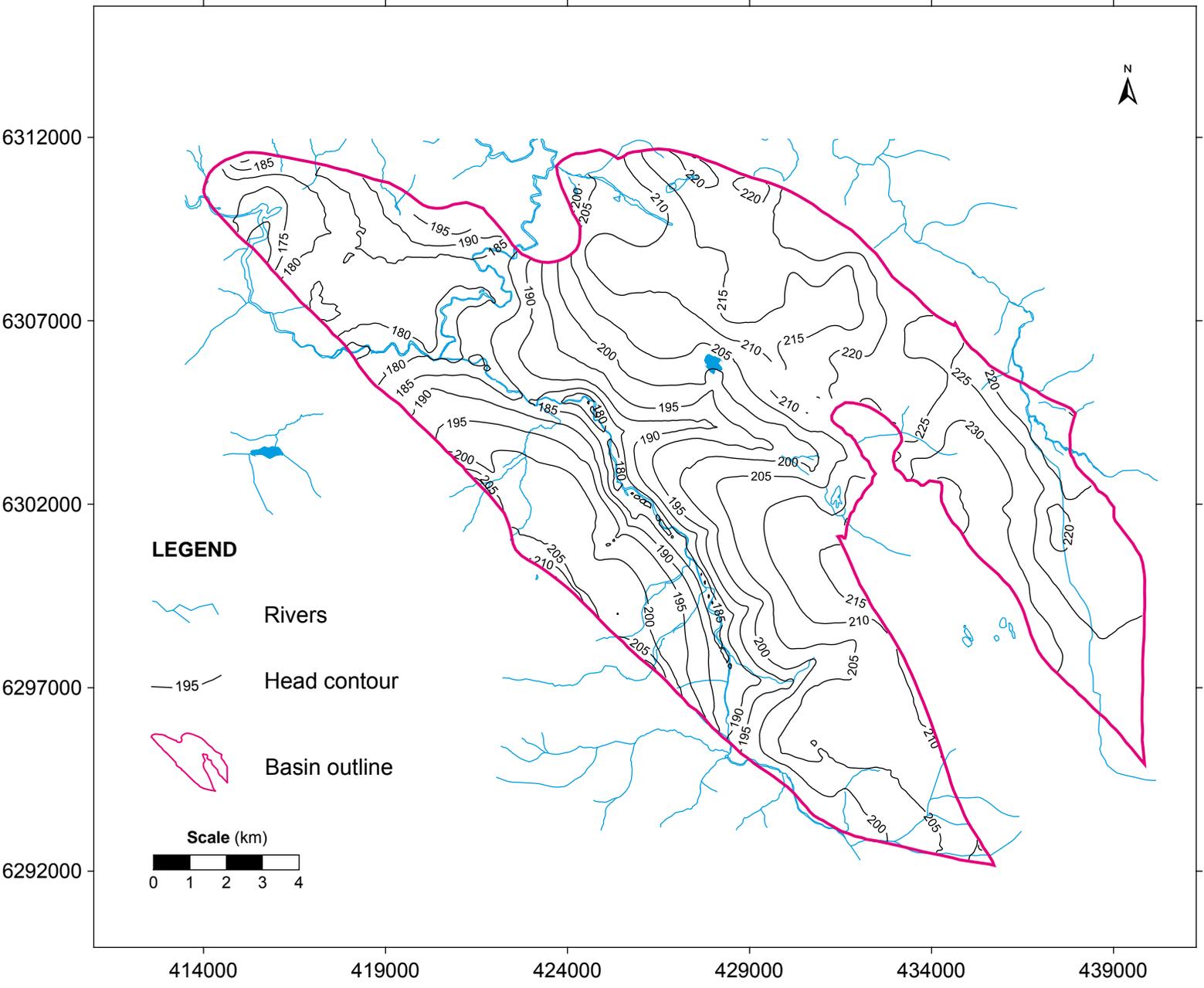


Figure D-1. Steady state water table

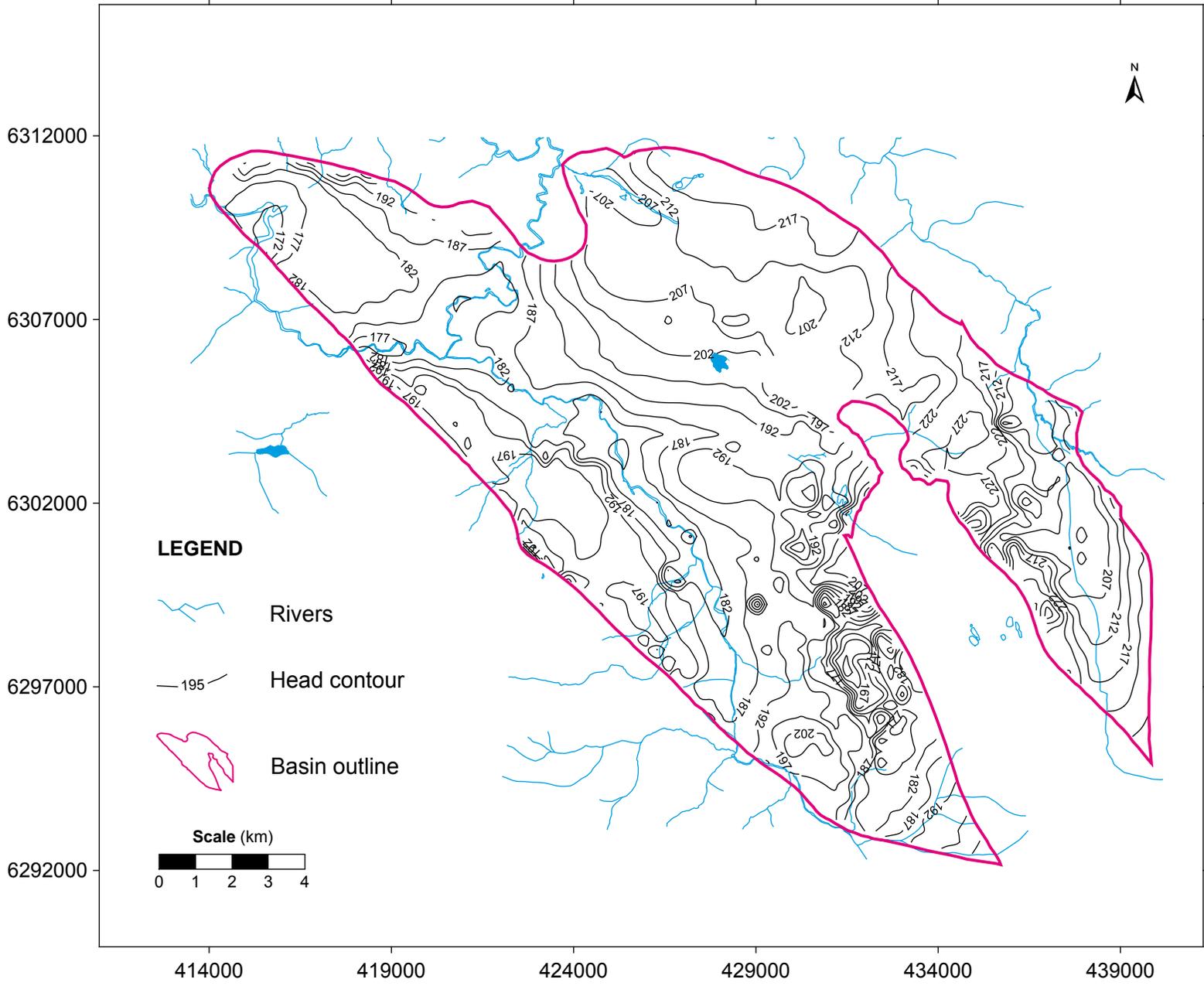


Figure D-2. Watertable 1999

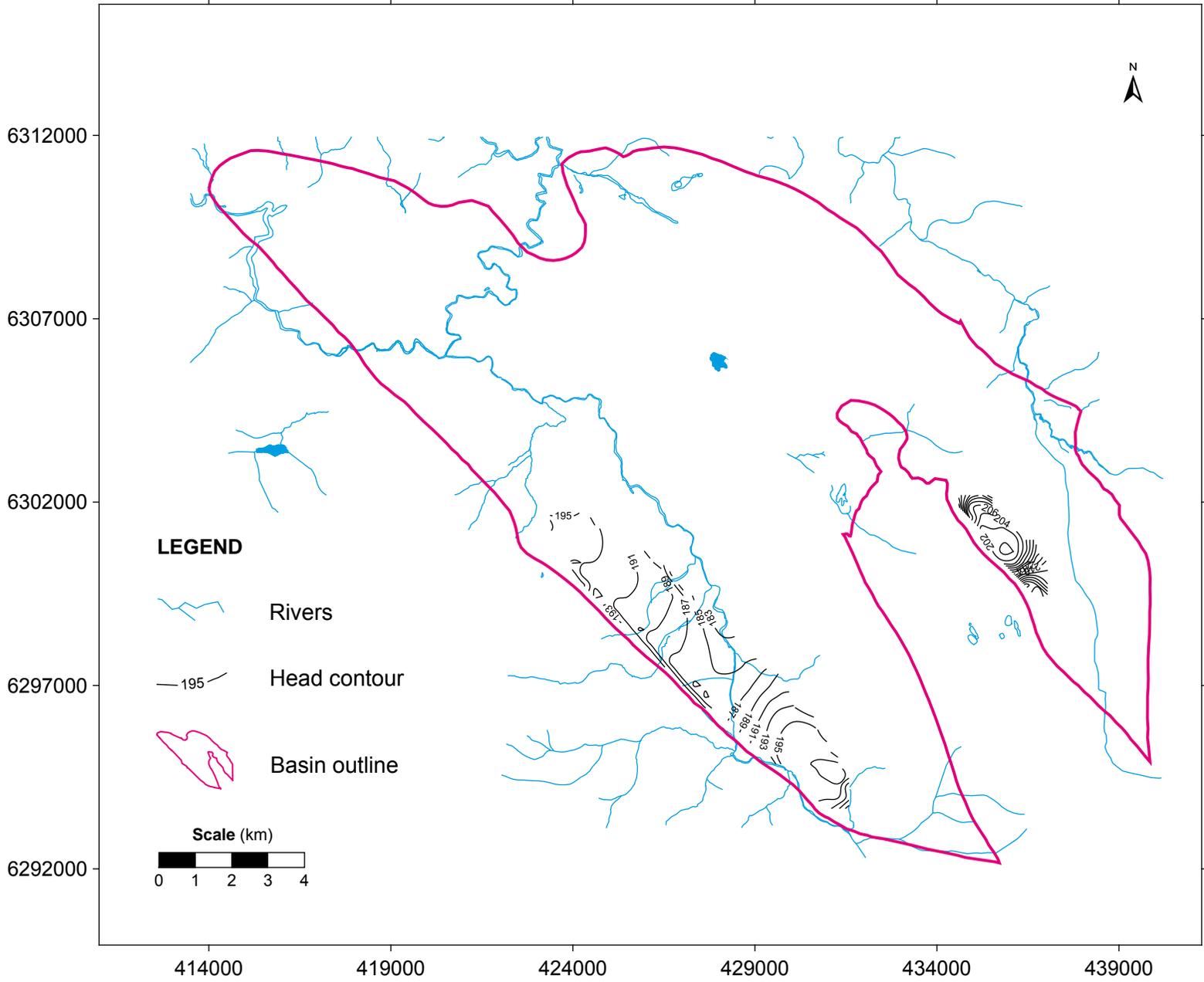


Figure D-3. Head Contour - Mujari (1999)

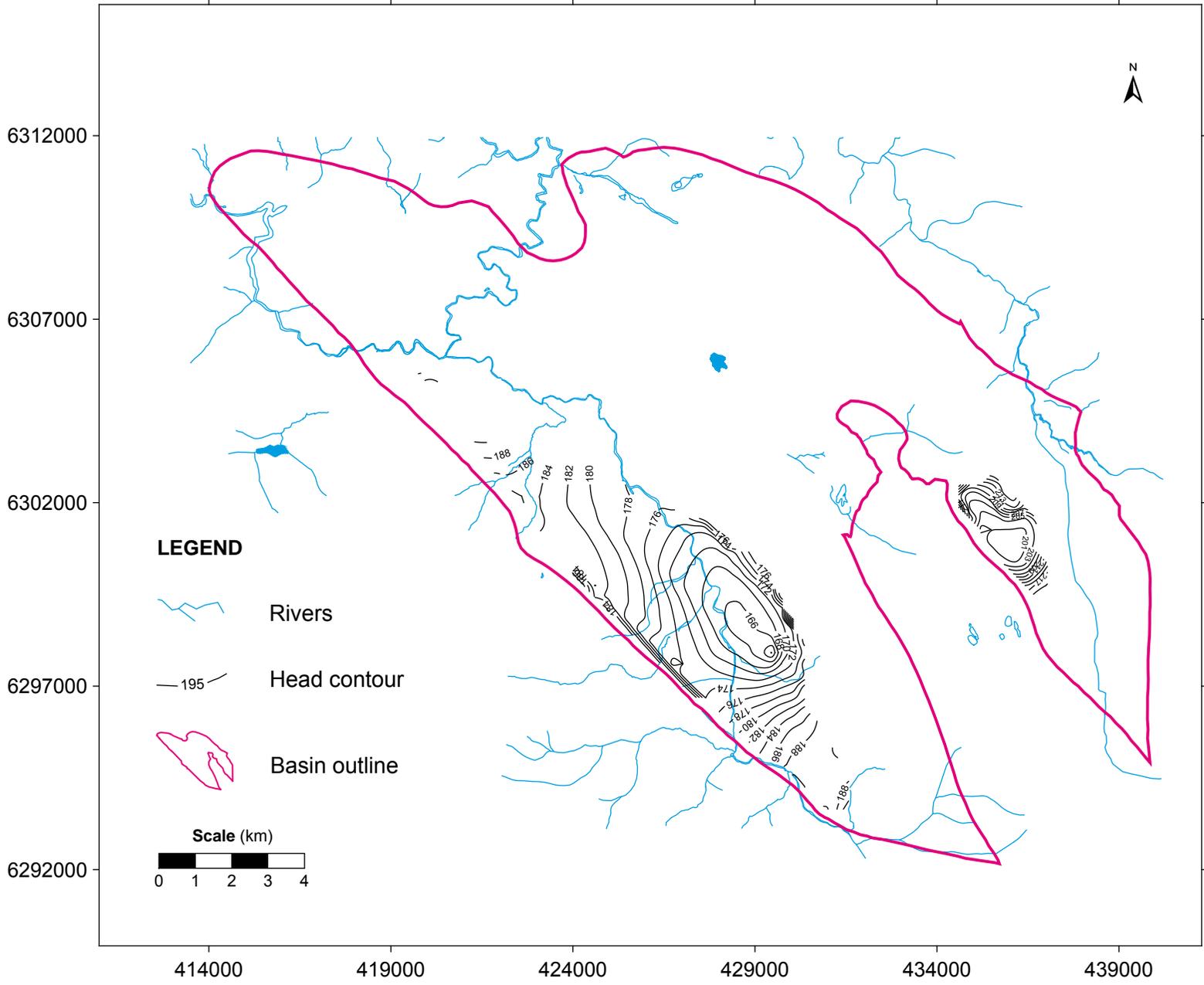


Figure D-4. Head Contour - Muja 2 Layer (1999)

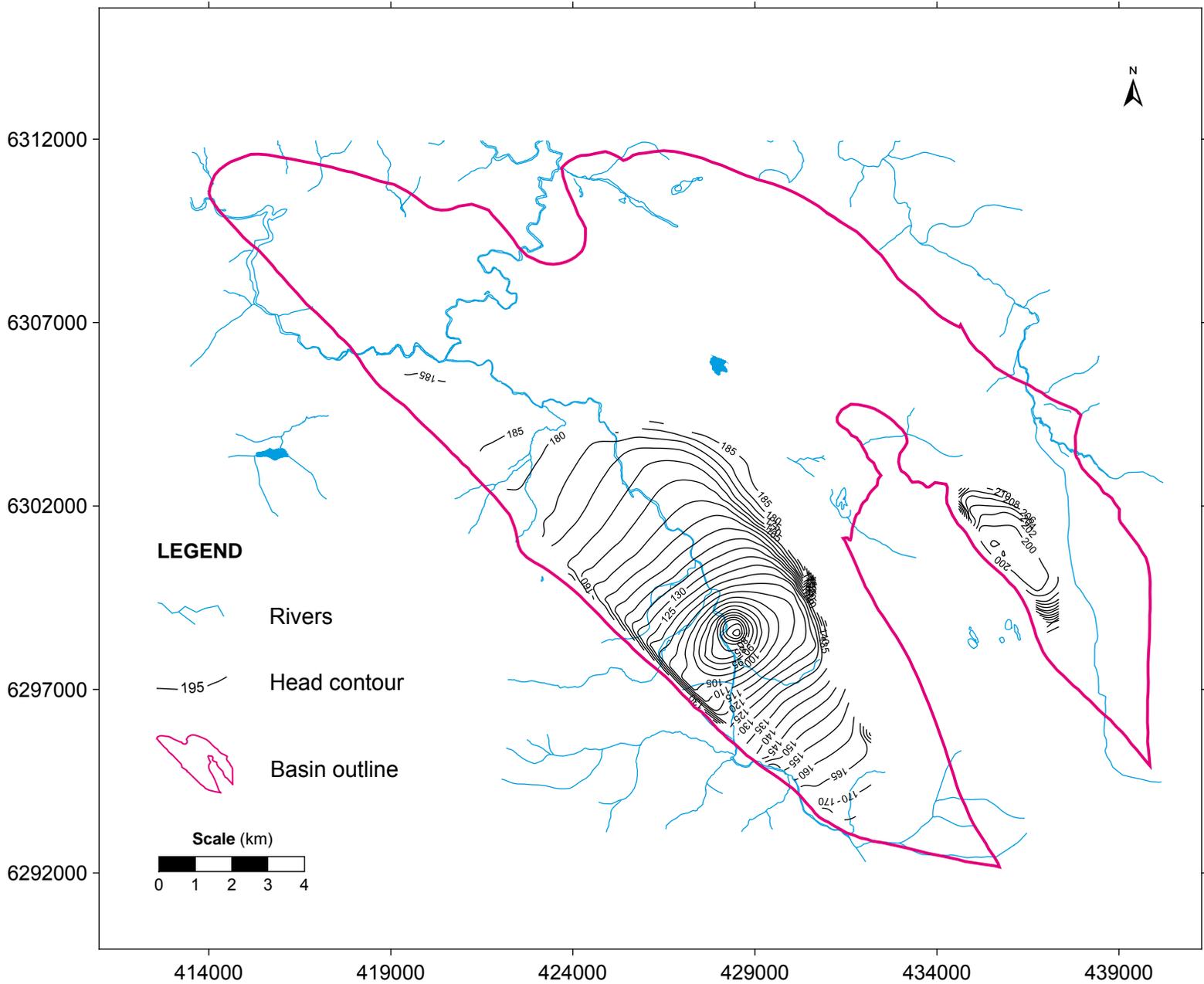


Figure D-5. Head Contour - Mujas3 Layer (1999)

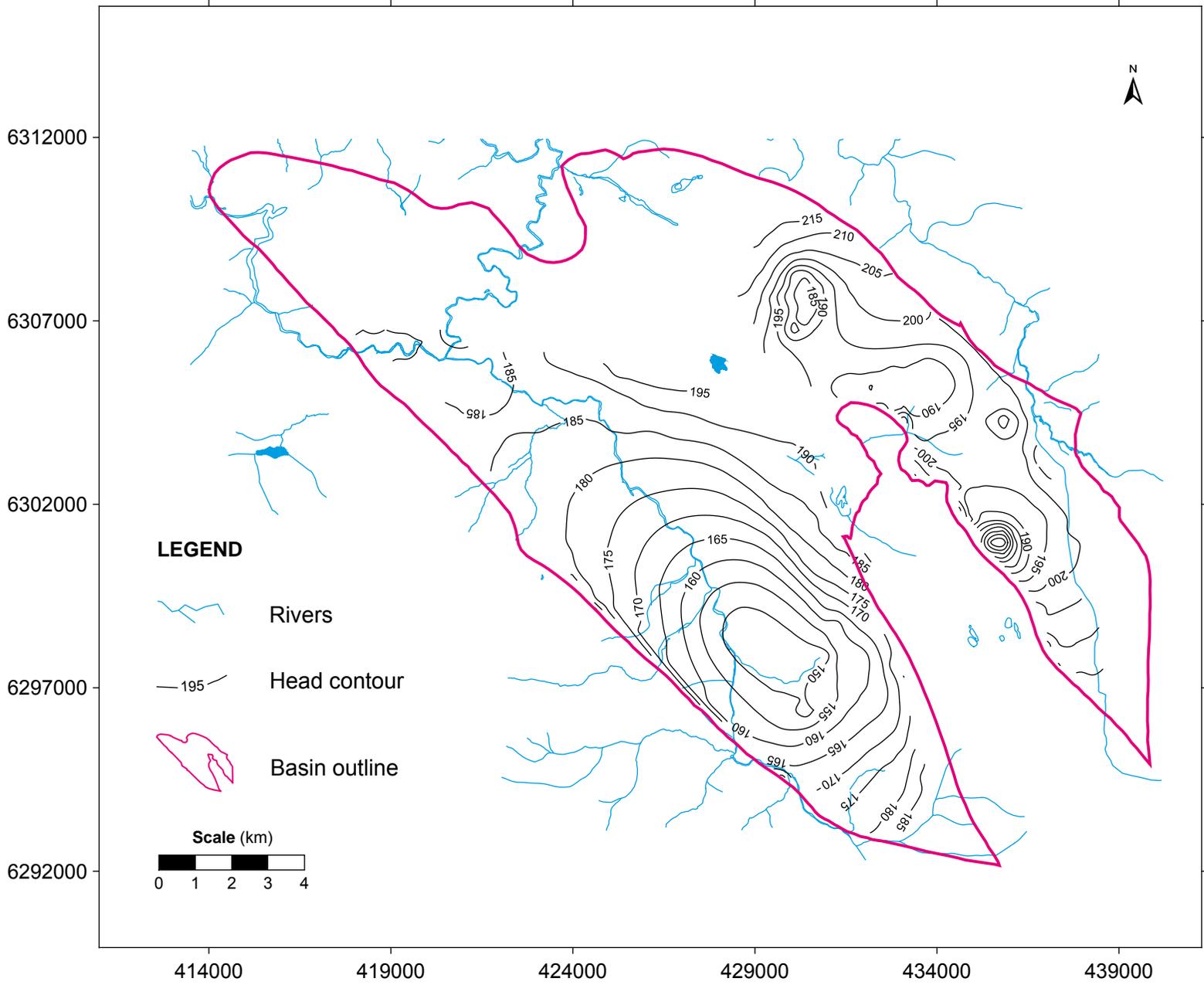


Figure D-6. Head Contour - Premier Coal Measures (1999)

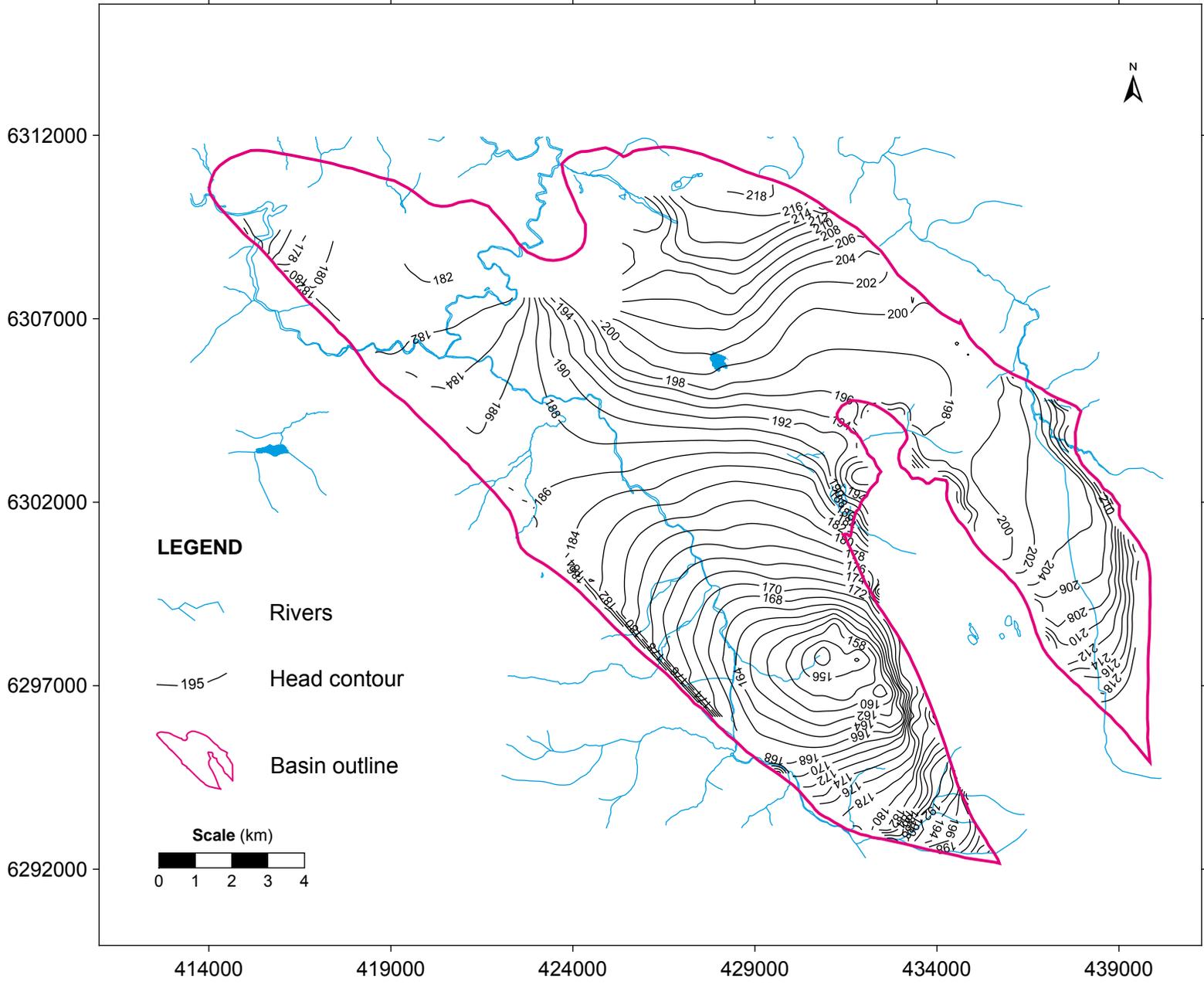


Figure D-7. Head Contour - Allanson Sandstone (1999)

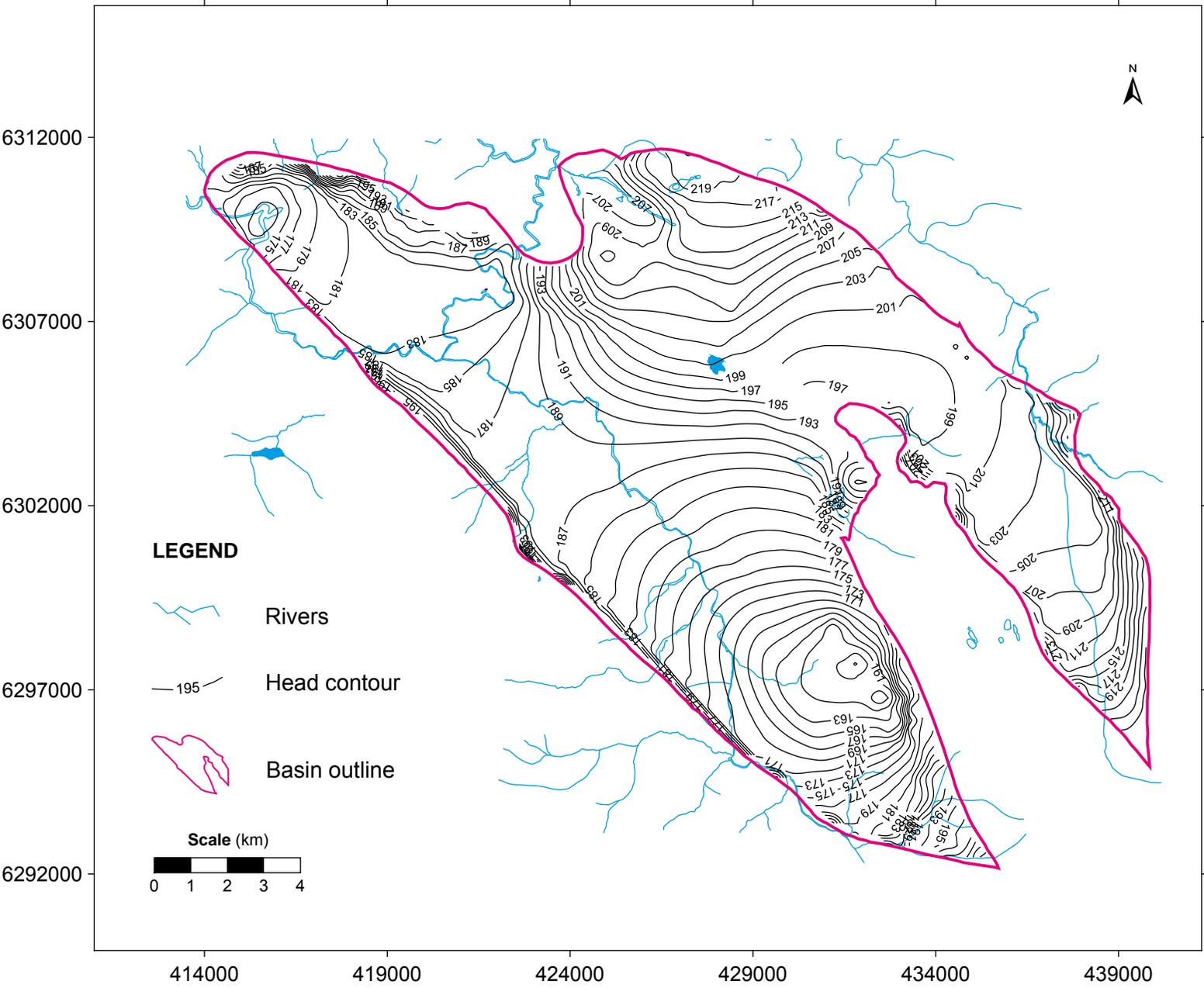


Figure D-8. Head Contour - Ewington Coal Measures (1999)

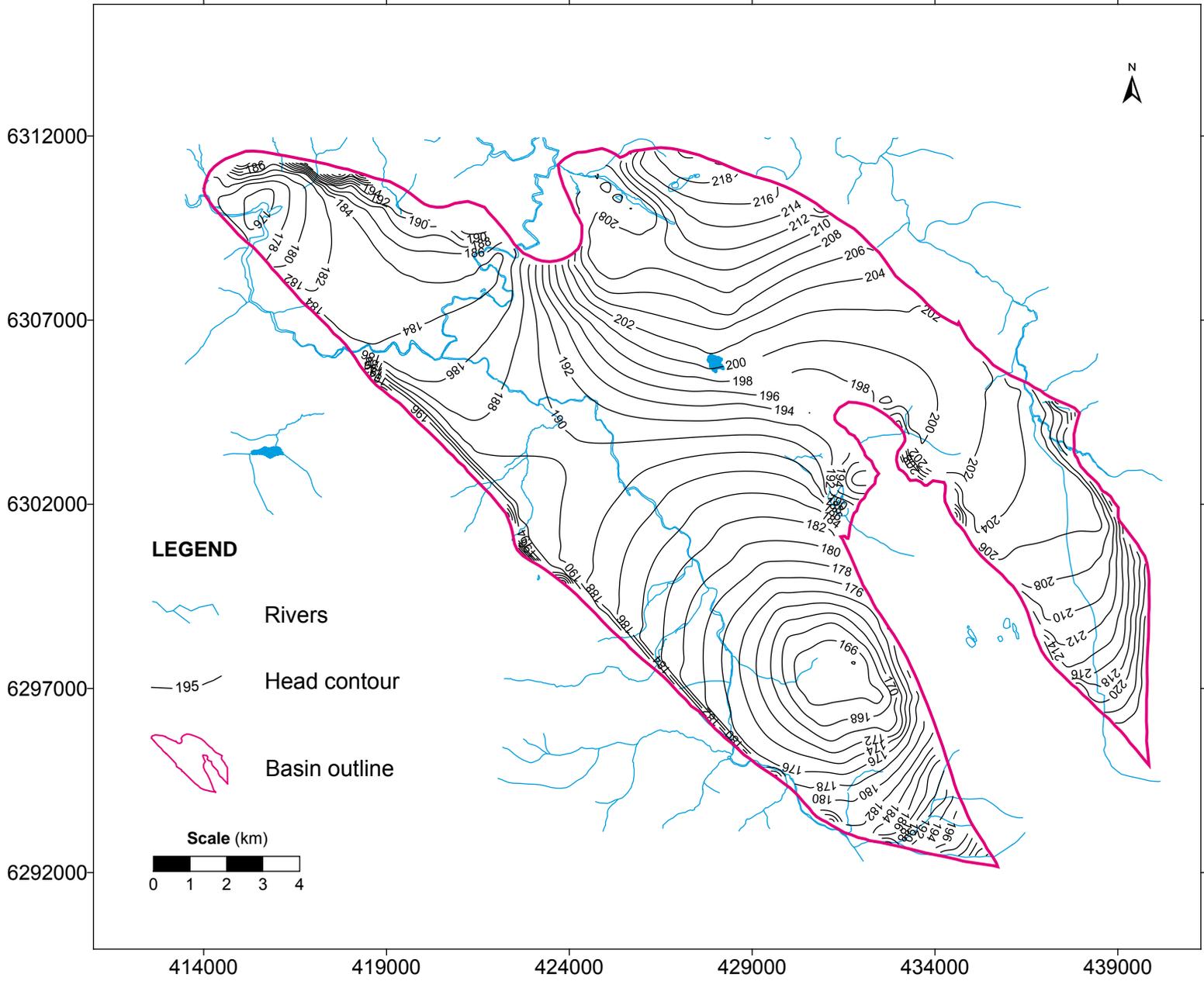


Figure D-9. Head Contour - Westralia Sandstone (1999)

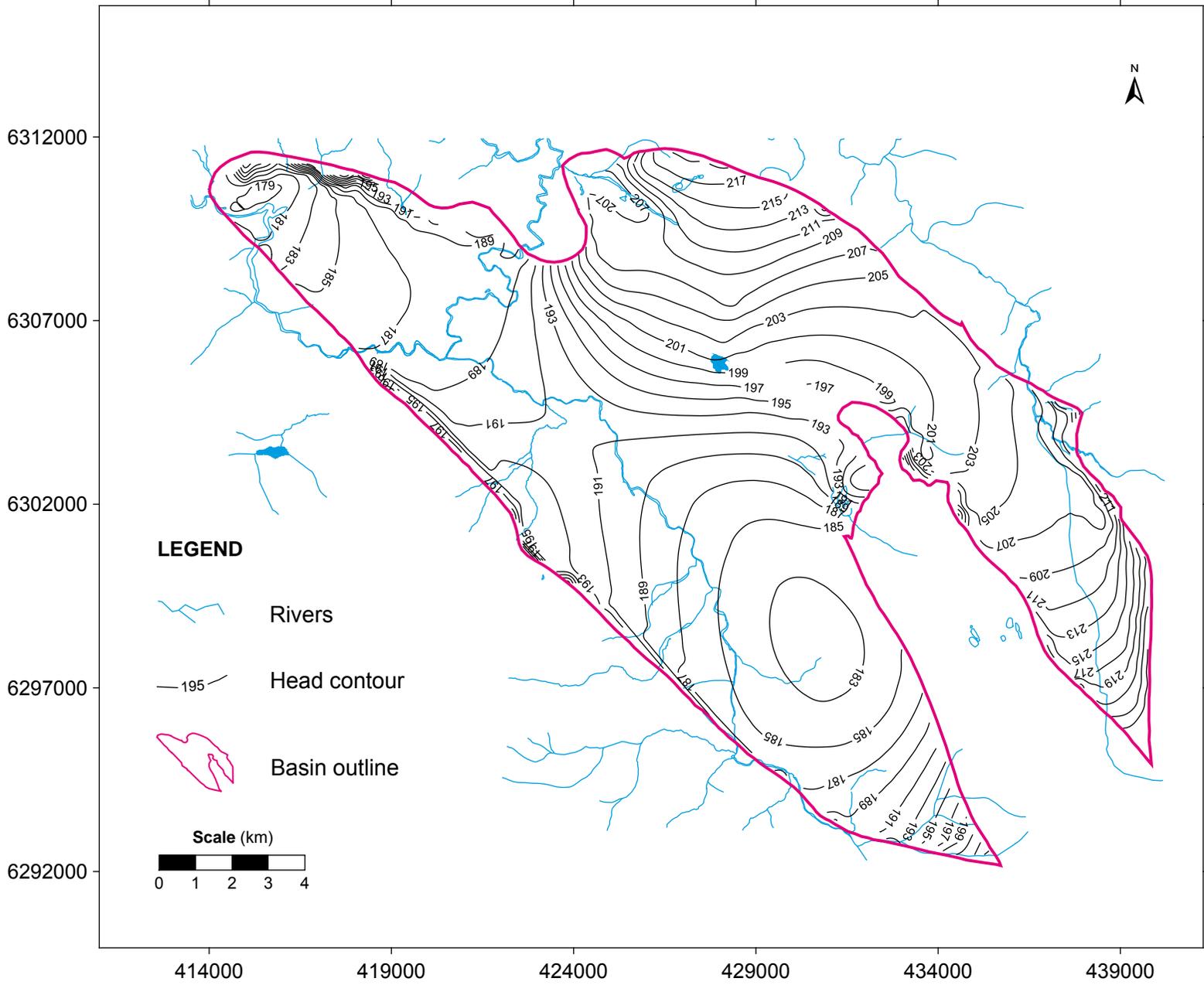


Figure D-10. Head Contour - Stockton Group (1999)

# Glossary

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

<b>Fault</b>	A fracture in rocks or sediments along which there has been an observable displacement
<b>Flux</b>	Flow
<b>Formation</b>	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
<b>Hydraulic</b>	Pertaining to groundwater motion
<b>Conductivity</b>	The flow through a unit cross-sectional area of an aquifer under a unit hydraulic gradient
<b>Gradient</b>	The rate of change of total head per unit distance of flow at a given point and in a given direction
<b>Head</b>	The height of the free surface of a body of water above a given subsurface point
<b>Lacustrine</b>	Pertaining to, produced by, or formed in a lake
<b>Leach</b>	Remove soluble matter by percolation of water
<b>Permian</b>	An era of geological time; 225–280 years ago
<b>Porosity</b>	The ratio of the volume of void spaces, to the total volume of a rock matrix
<b>Potentiometric surface</b>	An imaginary surface representing the total head of groundwater and defined by the level to which water will rise in a bore
<b>Quaternary</b>	Relating to the most recent period in the Cainozoic era, from 2 million years to present
<b>Salinity</b>	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
<b>Scarp</b>	A line of cliffs (steep slopes) produced by faulting or by erosion
<b>Specific yield</b>	The volume of water than an unconfined aquifer releases from storage per unit surface area of the aquifer per unit decline in the watertable
<b>Storage coefficient</b>	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
<b>Syncline</b>	A basin shaped fold in sedimentary strata

<b>Tectonic</b>	Pertaining to forces that produce structures or features in rocks
<b>Tertiary</b>	The first period of the Cainozoic era; 2–65 million years ago
<b>Transmissivity</b>	The rate at which water is transmitted through a unit width of an aquifer under a unit hydraulic gradient
<b>Transpiration</b>	The loss of water vapour from a plant, mainly through the leaves
<b>Watertable</b>	The surface of a body of unconfined groundwater at which the pressure is equal to that of the atmosphere
<b>Well</b>	Large diameter bore, usually dug by hand

## Other publications in the HG Series

- HG 1** *A bibliography of published reports on groundwater in Western Australia.*  
Smith, M.G., Ansell, H. M., Smith, R. A.
- HG 2** *Groundwater resources of the Northern Goldfields, Western Australia.*  
Johnson, S.L., Commander, D.P., O'Boy, C.A.
- HG 3** *Hydrogeology of the Swan Coastal Plain between Cervantes and Leeman, Perth Basin.*  
Kern, A.M.
- HG 4** *Groundwater resources assessment of the Murchison region (in prep)*
- HG 5** *Hydrogeology and groundwater resources of the Collie Basin, Western Australia.*  
Varma, S.
- HG 6** *Hydrogeology of the Blackwood River catchment, Western Australia.*  
Ye, L., Smith, R.A., Rutherford, J.L., De Silva, J.
- HG 7** *Hydrogeology of the Ord River irrigation area.*  
O'Boy, C.A., Tickell, S.J., Yesertener, C., Commander, D.P., Jolly, P., Laws, A.T.
- HG 8** *Central Pilbara groundwater study.*  
Wright, A.H., Johnson, S.L.
- HG 9** *Mine void water resource issues in Western Australia.*  
Johnson, S.L., Wright, A.H.
- HG 10** *Groundwater investigation program in Western Australia (2005 to 2020).*  
Johnson, S.L., Commander, D.P., O'Boy, C.A., Lindsay, R.P.
- HG 11** *The hydrogeology of groundwater dependent ecosystems in the Northern Perth Basin.*  
Rutherford, J. L., Roy, V.J. Johnson, S.L.
- HG 12** *Hydrogeology of the Wilga Basin, Western Australia.*  
S.L. McHugh
- HG 13** *Assessment of The Artificial Maintenance of Groundwater in Yanchep Caves, Groundwater Flow Modelling.*  
C Yesertener
- HG 14** *Assessment of the Declining Groundwater Levels in the Gngangara Groundwater Mound.*  
C Yesertener



# Publication feedback form

The Department of Water welcomes feedback to help us to improve the quality and effectiveness of our publications. Your assistance in completing this form would be greatly appreciated.

Please consider each question carefully and rate them on a 1 to 5 scale, where 1 is poor and 5 is excellent (please circle the appropriate number).

**Publication title: Groundwater Model of the Collie Basin, Western Australia HG 15**

*How did you rate the quality of information?*                    1            2            3            4            5

*How did you rate the design and presentation of this publication?*                    1            2            3            4            5

*How can it be improved?*

.....  
.....  
.....

*How effective did you find the tables and figures in communicating the data?*                    1            2            3            4            5

*How can they be improved?*

.....  
.....  
.....

*How did you rate this publication overall?*                    1            2            3            4            5

*If you would like to see this publication in other formats, please specify. (eg CD)*

.....

*Please cut along the dotted line on the left and return your completed response to:*

**Communications Manager  
Department of Water  
PO Box K822  
Perth Western Australia 6842  
Phone: (08) 6364 7600  
Facsimile: (08) 6364 7601**





