FINAL REPORT
3 October 2005

Water Corporation

South West Yarragadee Aquifer

Peer Review Panel Report on South-West Aquifer Modelling System (SWAMS v 2.0)

October 2005

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Reference: 0035929

For and on behalf of Peer Review Panel

Paul Whincup Chairman	Phil Wharton Member	Richard Martin Member

Date: 3 October 2005

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EXECUTIVE SUMMARY

An Expert Peer Review Panel (the Panel) comprising three independent hydrogeologists was appointed in August 2005 by the Water Corporation to Peer Review the Conceptual and Numerical Hydrogeological Models of the Southern Perth Basin. The numerical model has the acronym SWAMS (South-West Aquifer Modelling System). The Panel has utilised data available to the end of August 2005 and has reviewed the most recent version of SWAMS v 2.0.

The same Panel had previously been appointed by the Department of Environment (DoE) in June 2003 to review an earlier version of SWAMS (v 1.2.1) which utilised information available up to August 2004. The Peer Review Panel presented its report on SWAMS v 1.2.1 to DoE in December 2004.

In that report the Panel identified where further work would clarify some uncertainties identified in both the conceptual and numerical models and enhance their validity. Most of the recommendations of the Panel applied to more detailed analysis of existing data and were considered capable of being addressed cost effectively within a relatively short time frame.

The Panel's recommendations for SWAMS v 1.2.1 have been implemented and indeed expanded by Water Corporation. Considerable effort has been employed in updating allocation data in terms of aquifer identification and actual abstraction. A large number of existing data points have been reviewed to refine and update the distribution of geological units. Additional investigative drilling has also been completed in the St Johns Brook, Poison Gully (Blackwood River) and Reedia areas.

Improvements to the SWAMS v 1.2.1 model incorporated into v 2.0 have included the following:

- Modification of geology, layering, faults and boundary conditions;
- Use of environmental heads;
- Use of the Drain software package to represent all major rivers;
- New zonations for parameters and recharge;
- New time series scaling factors for abstraction and recharge;
- Introduction of horizontal anisotropy; and
- Representation of evapotranspiration on the coastal plains.

The updated SWAMS v 2.0 is therefore a considerable enhancement of SWAMS v 1.2.1.

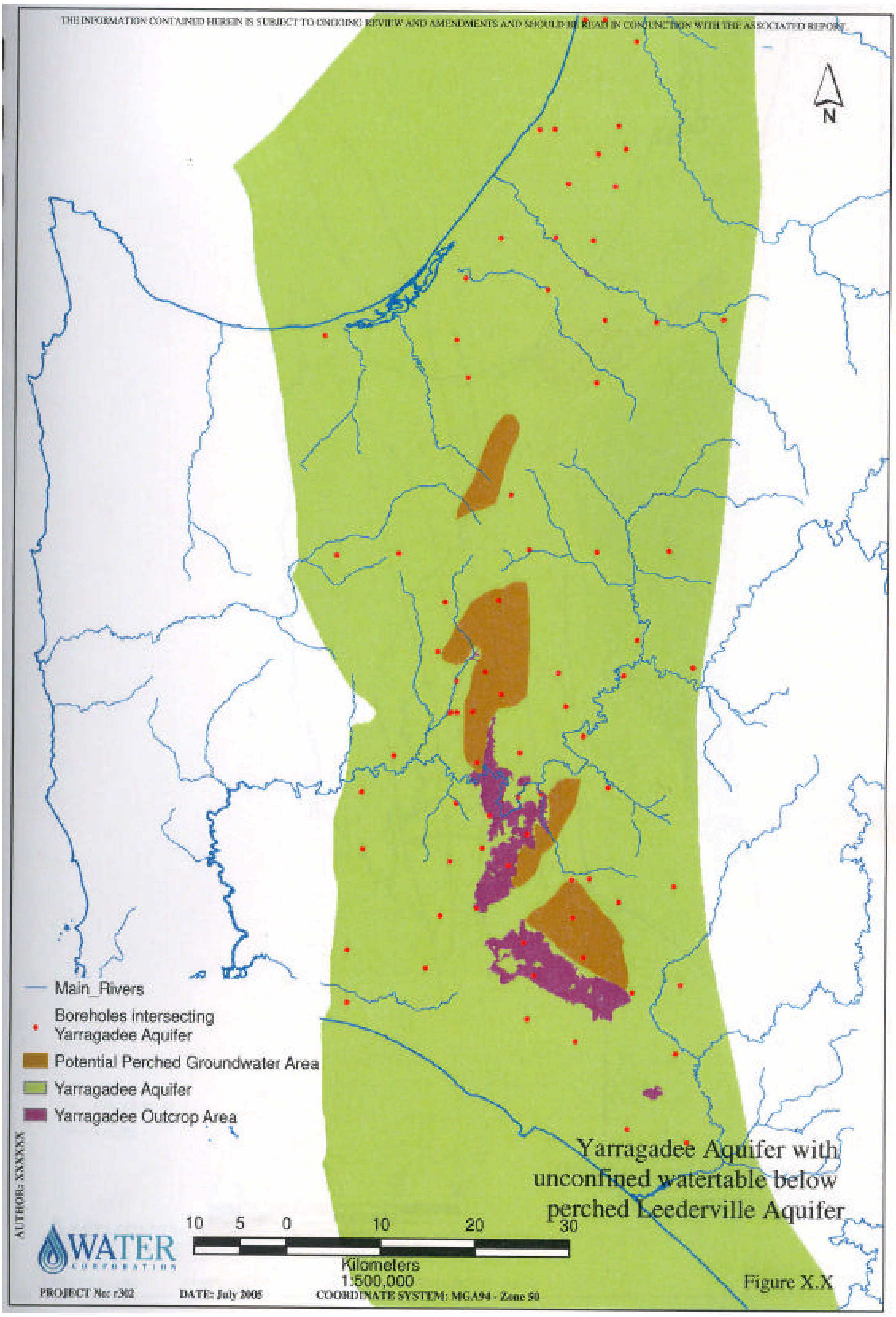
The Panel believes that the investigative work and inputs to the conceptual hydrogeological model particularly in relation to the Yarragadee aquifer (Juy) are of a high standard. The overlying Leederville aquifer, low permeability units between the Leederville and Yarragadee aquifers, and adjacent aquifers to the west are more complex than the Yarragadee aquifer itself and are therefore difficult to adequately represent within the conceptual model and by inference into the numerical model.

In general the Panel concludes that the generalities incorporated into the model have built an element of conservatism into SWAMS v 2.0.

The model domain for SWAMS v 2.0 is 190 km long by 70 km wide and covers an active area of 8,500 km^2 of which some 6,000 km^2 is onshore. The Yarragadee occupies 7,260 km^2 of the model area of which 4,885 km^2 is onshore.

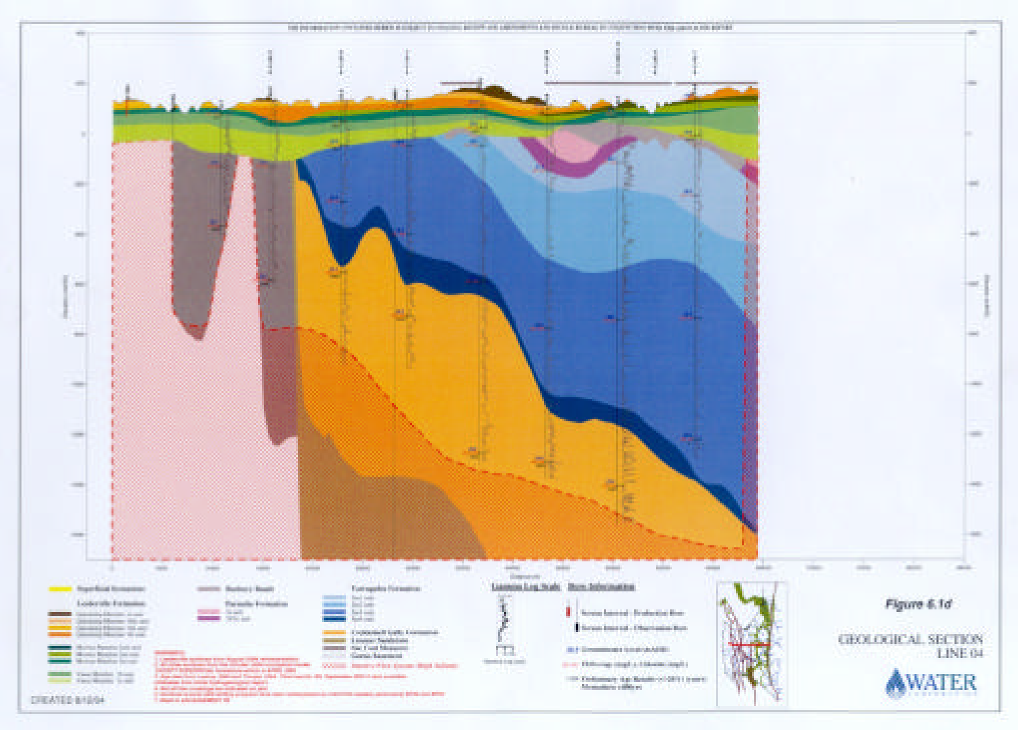
The surface geology of the Yarragadee aquifer depicted on *Figure ES.1* shows an area of outcrop near the central southern part of the model, coincident with the groundwater divide. This is the area where direct rainfall recharge occurs. Over the larger part of the modelled area the aquifer is recharged by leakage from the overlying Leederville aquifer and other adjacent aquifers.

Figure ES.1 Modelled Extent of Yarragadee Aquifer



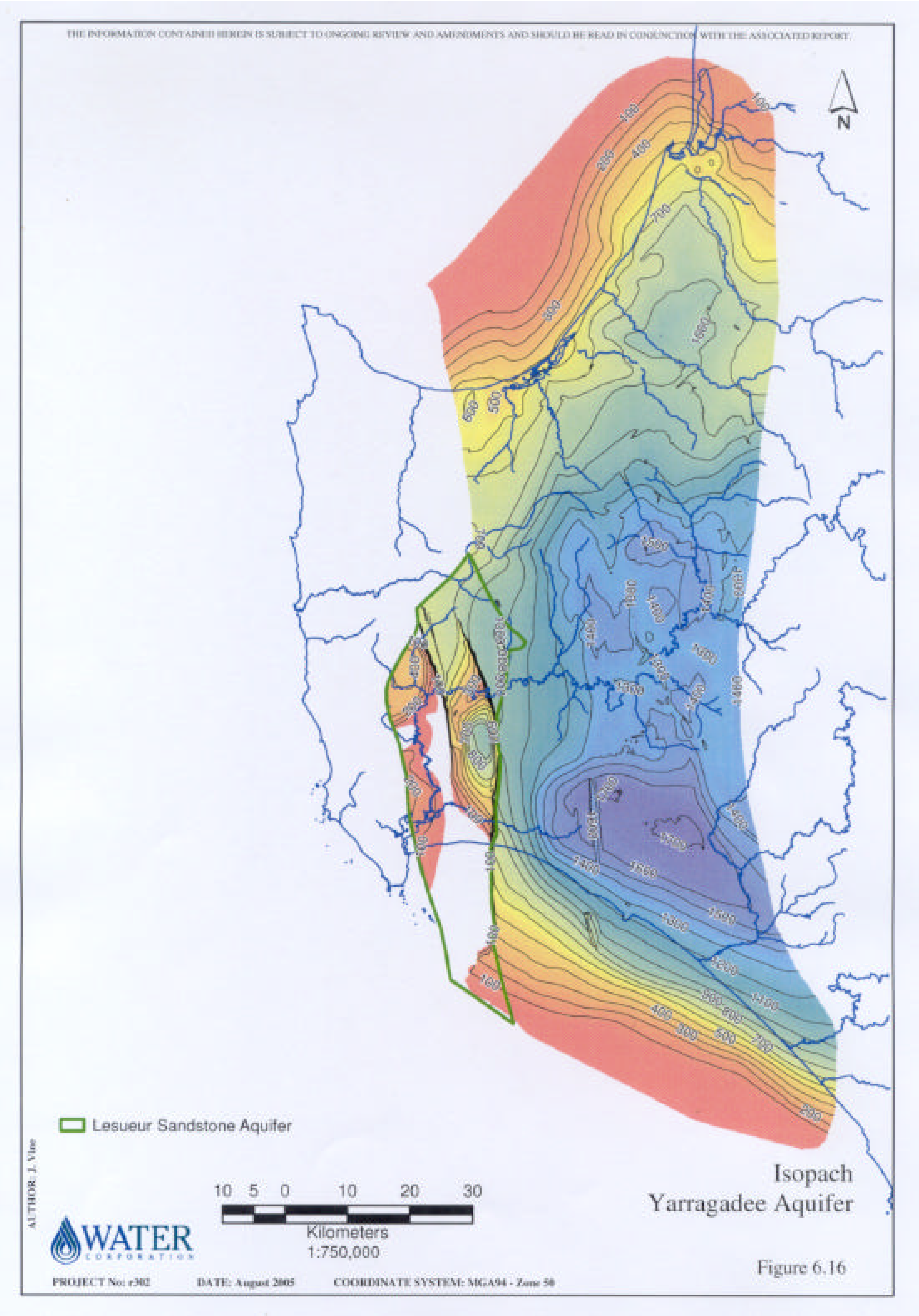
The geological cross-section shown in *Figure ES.2* also shows the Yarragadee aquifer thickening to the east and attaining a depth of 1,800 m below ground level. This eastern area is close to that selected for the proposed Eastern Borefield.

Figure ES.2 Geological Cross-Section



The isopachs (lines of equal aquifer thickness) for the Yarragadee aquifer shown in *Figure ES.3* indicate the greatest thickness beneath the area of outcrop of units Juy2 and Juy3 near the groundwater divide with thicknesses exceeding 1,700 m. Thicknesses rapidly decline towards and beyond the south coast and more gradually northwards.

Figure ES.3 Isopachs of Yarragadee Aquifer



Eight hydrogeological layers have been conceptualised into the model of which the lowermost five units are principally Yarragadee aquifer, extending from Juy1 (allocated to two layers), through Juy2 and Juy3 to the deepest part of the aquifer in Juy4. The Water Corporation proposal is to abstract groundwater from a combination of Juy1 and Juy3. This major aquifer contains groundwater with a salinity of less than 1,000 mg/L total dissolved salts suitable for municipal water supply to a maximum depth of about 1,800 m which represents the base of the active flow system.

On that basis the Yarragadee aquifer holds a very large volume of low salinity groundwater in storage, estimated to be in excess of one million (1,000,000) GL at a porosity of 20% not including additional large volumes of low salinity groundwater held in overlying, underlying, adjacent and interbedded clayey formations where aquifer porosities are higher, between 30% and 50%. These clayey sediments will leak water into the Yarragadee aquifer when groundwater heads are lowered during abstraction. This leakage will occur over a very large area and contribute significantly to the capacity of aquifer to meet increased demands. These additional stored resources are not included in the SWAMS v 2.0 model and provide a degree of conservatism when projecting drawdown levels under different abstraction scenarios.

The very large reserves of stored groundwater need to be assessed in terms of their potential contribution in the event of substantial reductions in long term rainfall.

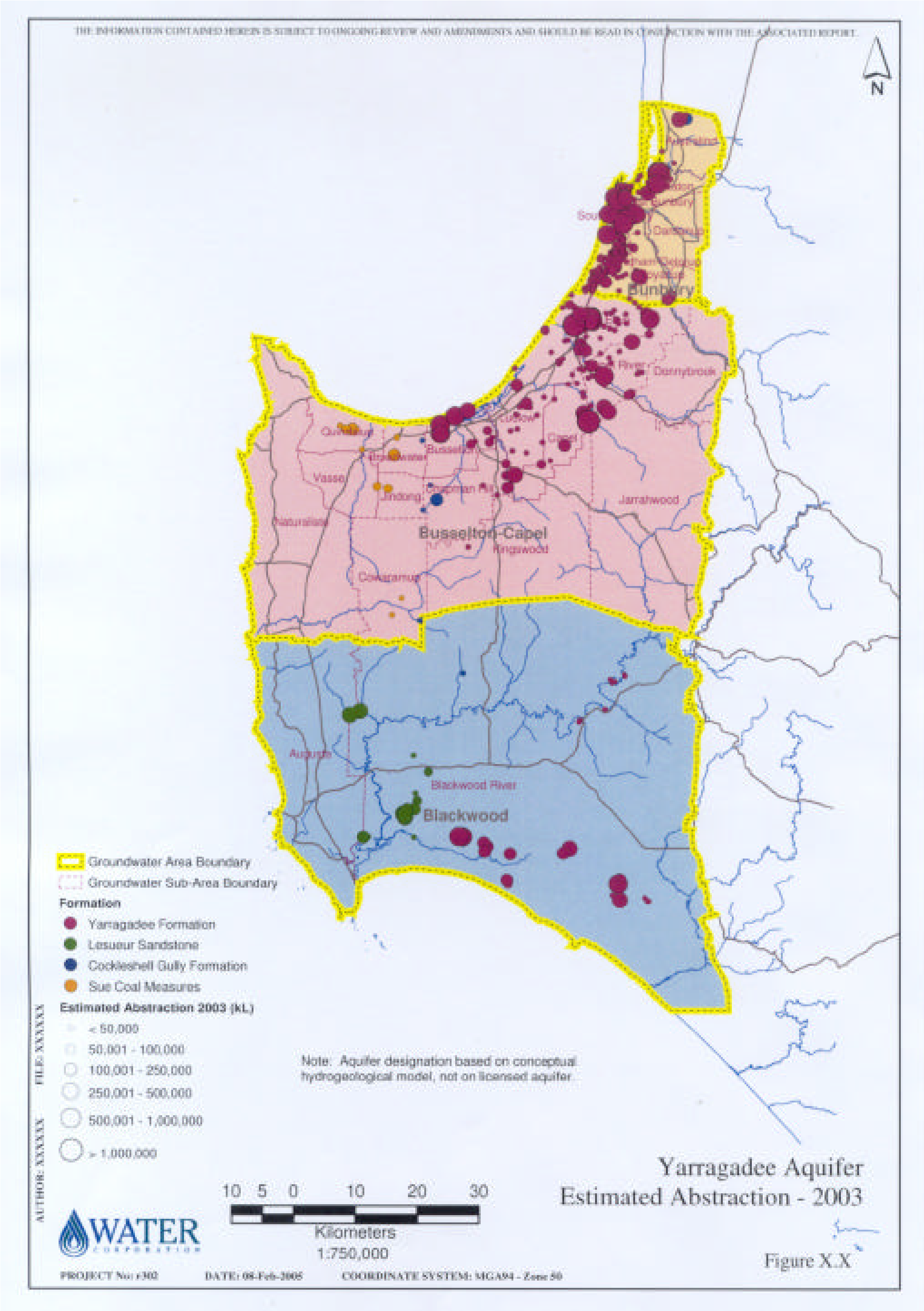
As part of the update to SWAMS v 2.0 the net recharge estimation has been revised and compared against a chloride balance and three different recharge and water balance models (WEC-C, WAVES and WATBAL). Using the average rainfall data for the last 20 years the four recharge estimates for the model domain range between 282 and 340 GL/annum. Given the approximations in each model these separate estimates support the recharge value of 374 GL/annum calculated in SWAMS v 2.0.

During 2003 there were 3,166 licensed bores, including 184 large capacity bores, operating within the area covered in the model domain (*Figure ES4*). The majority are concentrated along the northern (Swan) coastal plain with a lesser number along the southern (Scott) coastal plain.

The Year 2003 abstraction from the Yarragadee aquifer was estimated at 36.9 GL, from the Leederville Formation Aquifer 18.0 GL, and from the superficial aquifers 7.1 GL. This total of 62.0 GL compares to an estimated abstraction of 36.0 GL in 1990.

Regional abstractions for the next 30 years from the groundwater model area, exclusive of any Water Corporation abstraction, are projected to reach 158.7 GL by 2033 primarily from the Yarragadee aquifer along the Swan Coastal Plain in the northern part of the model domain, with a significant but lesser growth within the Scott Coastal Plain in the south. The bulk of the Yarragadee aquifer on the Blackwood Plateau (from which the Water Corporation plans to abstract water), is located in State Forest with only isolated pockets of private land and private groundwater abstraction is not permitted over most of this area.

Figure ES.4 Yarragadee Estimated Abstraction 2003



SWAMS v 2.0 was calibrated over the period 1990 to 2003 using 337 monitor bores and indicated some improvement when compared to SWAMS v 1.2.1. However difficulty in calibrating to heads in the Mowen aquitard and Leederville aquifer reflects the complexity of these systems compared to the Yarragadee aquifer. The maximum positive error for the Yarragadee aquifer was 13 m with a maximum negative of 9 m and average absolute error of 3.1 m. This indicates that SWAMS v 2.0 is predicting water level changes under existing abstraction conditions for the Yarragadee aquifer over the period 1990 to 2003 within plus or minus 3 m of the observed drawdowns in the majority of monitor bores calibrated.

Comparison of modelled and observed annual drainages for the Blackwood, Donnelly and Scott Rivers and the Swan Coastal Plain indicated a much higher modelled drainage in the Blackwood River between Nannup and Hutt Pool than observed (59.5 GL/annum modelled compared to 24.0 GL/annum observed) and similarly for the Donnelly River (22.2 GL/annum modelled compared to 6.0 GL/annum observed).

The flow comparisons for the Blackwood River in the Yarragadee outcrop area and for the Scott River showed close agreement between modelled and observed readings but those for the Swan Coastal Plain did not match. The disparities for the Blackwood and Donnelly Rivers need further explanation.

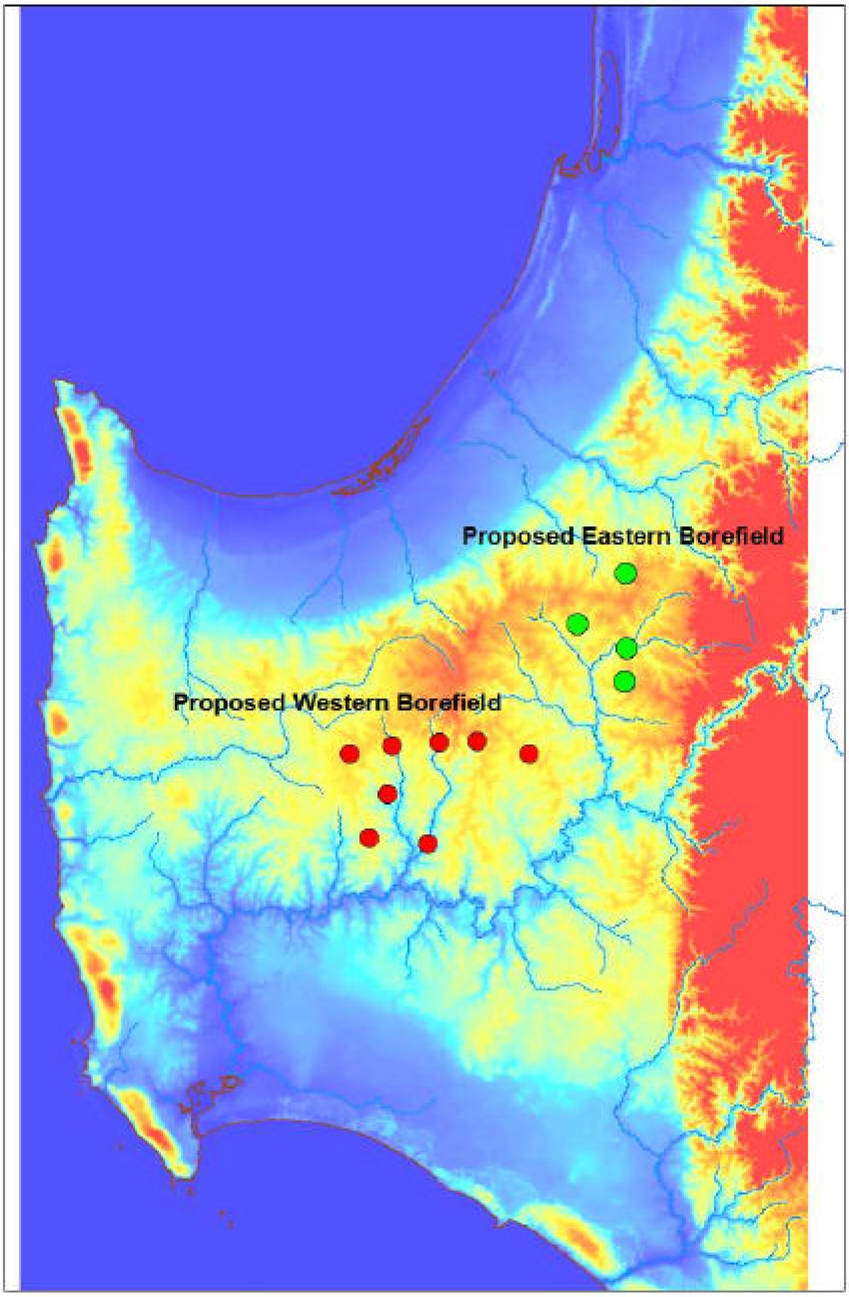
The Swan Coastal Plain is complicated by irrigation flow returns, which are not included in the model, and by lack of monitoring data for a number of drains.

Partial validation of the calibrated model has been undertaken by simulating flow paths in the Juy3 unit of the Yarragadee aquifer. This simulation back tracks in 1,000 year increments from the northern and southern shorelines and confirms that recharge is principally from the known Yarragadee outcrop and hence recharge area. These are then compared to observed Carbon 14 age datings which indicate that groundwater at Bunbury for example is about 23,000 years old, whereas at the southern coast where the flow path is much shorter, the groundwater is less than 10,000 years old. The simulated ages are consistent with measured ages confirming that SWAMS v 2.0 can be used in a broad regional context.

SWAMS v 1.2.1 was originally used to calculate drawdowns from a proposed borefield (Western Borefield, *Figure ES5*) at Rosa Brook near the Blackwood River at the site of the large capacity test bore constructed in unit Juy3 of the Yarragadee aquifer. The output of the model indicated high reductions in water levels in environmentally sensitive areas.

SWAMS v 2.0 has subsequently been used to calculate drawdowns under ten different abstraction scenarios including scenarios with a 5% and 10% reduction in recharge. The scenario with least impact on existing and future users and to groundwater dependent ecosystems and environmental water flows is the Eastern Borefield with an abstraction of 22.5 GL/annum from each of units Juy1 and Juy3 of the Yarragadee aquifer. This scenario under continuing average recharge conditions contributes an additional one to two metres of drawdown to groundwater heads in the Yarragadee aquifer on the Swan Coastal plain, where the majority of current and future groundwater abstraction is projected to occur, and a small decline in groundwater discharge to the Blackwood River. Modelling indicates that abstraction from unit Juy3 alone would contribute additional drawdown to private users, mainly on the Swan Coastal Plain. By splitting the abstraction with the shallower unit Juy1 the modelling indicates a decline in near-surface groundwater levels and a decline in flow to St John Brook.

Figure ES.5 Proposed Borefield Locations



The modelled water balance of the study area under average recharge conditions indicates a gross recharge of 632 GL/annum which under the regional growth scenario suggests that 234 GL/annum is lost as evapotranspiration (and/or drainage) on the Swan and Scott coastal plains and 398 GL/annum is net recharge. SWAMS v 2.0 predicts that with the addition of 45 GL/annum abstraction from the Eastern Borefield the evapotranspiration reduces to 227 GL/annum and net recharge increases to 405 GL/annum. Of the 45 GL/annum abstraction, 13 GL comes from reduced ocean outflow, 19 GL is derived from storage in the aquifer, 6 GL is from increased net recharge and 7 GL is from reduced outflow, mostly from the Blackwood River. An evapotranspiration component for the Blackwood River needs to be incorporated into the model to justify these estimates.

The Panel considers that the conceptual hydrogeological model for the Leederville aquifer may be unnecessarily complex and could be simplified into fewer layers. Similarly, for Yarragadee aquifer units Juy1, Juy2, Juy3 and Juy4.

The Panel recommends that the conceptual model within SWAMS 2.0 be updated as more hydrogeological data become available from geological mapping and investigative drilling. Similarly for the numerical model, as longer term monitoring of abstraction and water level changes become available.

Other improvements will result from the elimination of dry cells in the model, simulation of evapotranspiration on the Blackwood Plateau and incorporating the impact of flooding and irrigation water returns on the coastal plains.

The Panel concludes that the level of complexity of the aquifer distribution is not yet fully understood and the aquifer parameters for horizontal and vertical permeability are based on sparse data points particularly over the major part of the study area beneath the Blackwood Plateau where private large-scale groundwater abstraction is restricted. This limits the use of the model in defining drawdowns to the more accurate level normally required for assessing absolute impacts to groundwater dependent ecosystems, environmental water flows and other environmentally sensitive areas.

The Panel considers that the probability of substantial leakage to the producing aquifers from adjacent clayey formations, the contribution from rejected recharge in high water table regions of the Swan and Scott Coastal Plains, and the increasing recharge from recycled irrigation waters on the Swan and Scott Coastal Plains all serve to produce a degree of conservatism in the model output. In effect the Panel considers that under average rainfall conditions actual drawdowns will be less than projected.

Taking these factors into consideration the Panel believes that the sustainability of the aquifer in terms of groundwater resources and availability relies on more than solely recharge from rainfall in the outcrop areas.

The Panel considers that SWAMS v 2.0 has been developed to a stage where it can be used with some degree of confidence to evaluate the risks associated with growth in regional groundwater demand and alternative Water Corporation borefield scenarios. Its use should be as a Risk Management Tool whereby potential impacts are predicted, the consequent risks evaluated and where risks are considered untenable, either alternative scenarios are developed or risk monitoring and management procedures are put in place.

The Panel notes that the model has already been used to relocate the proposed Western Borefield to the east-northeast in order to reduce potential impacts to the Blackwood River and Reedia Wetlands. The model has also been used to assess impacts associated with the proposed Eastern Split Borefield in order to minimise drawdowns to existing and future users on the Swan Coastal Plain and potential impact to sensitive environmental areas on the Blackwood Plateau.

The Panel believes that SWAMS 2.0 is a suitable tool for evaluating borefield layout and for development of a local model which in turn can be used to optimise bore abstraction rates and pumping water levels.

The Panel expresses some reservation on use of Juy1 in the proposed Eastern Split Borefield based on interpretation of available information which indicate lower permeabilities and lower water quality than in the deeper units of the Yarragadee aquifer and suggest that at the appropriate time a more rigorous evaluation of the Eastern Split Borefield scenario be undertaken using a local more detailed model based on SWAMS v 2.0.

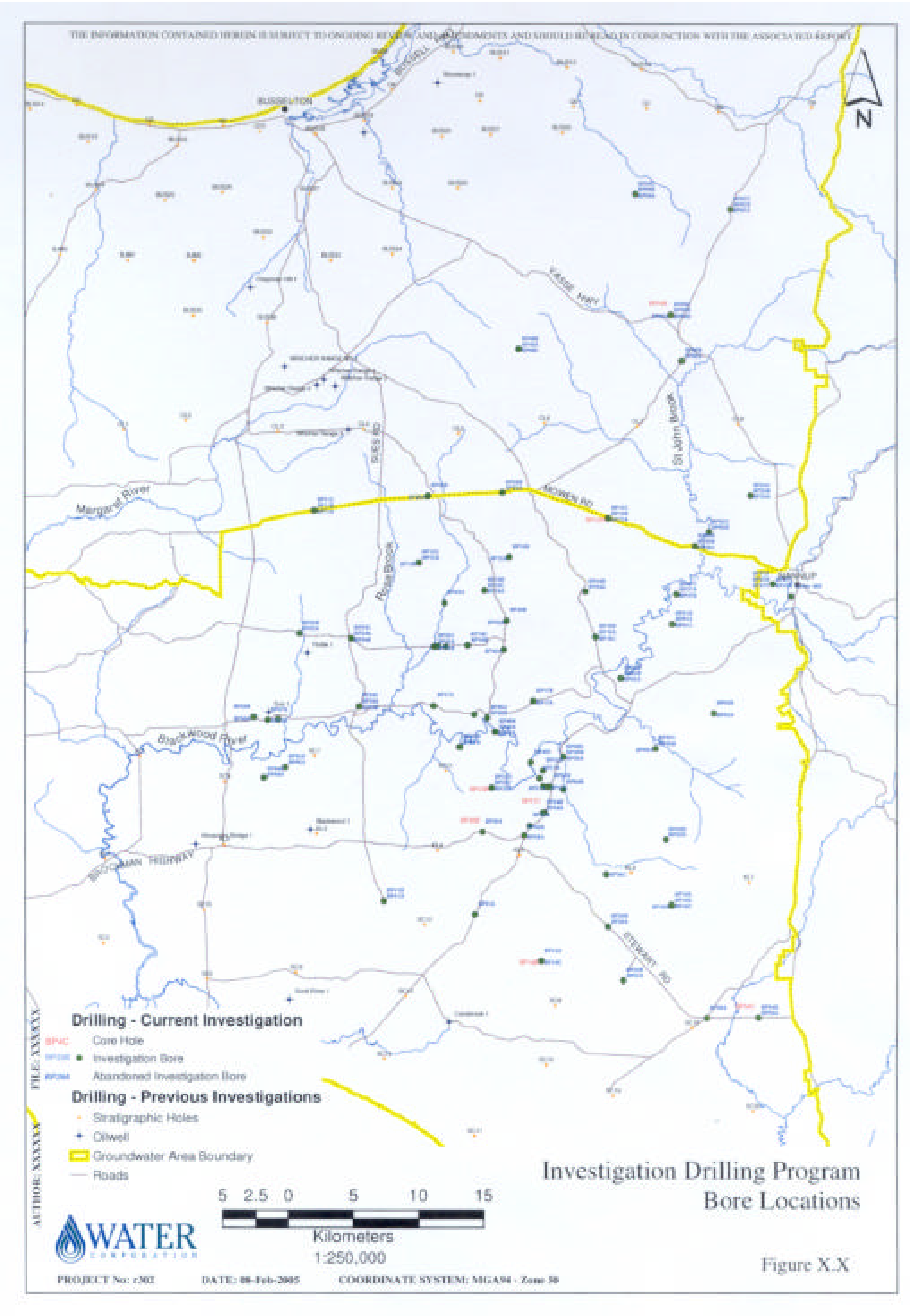
The Panel believes that although the potential for acid sulphate soil formation on the Scott Coastal Plain has been addressed and partly influenced the decision to move the proposed borefield to the north-east a similar exercise needs to be conducted for other areas including the Swan Coastal Plain.

In addition the Panel recommends that SWAMS v 2.0 be used to evaluate the impact of reduced long term rainfalls on water levels and river discharge under existing and projected abstraction scenarios.

1 *INTRODUCTION*

The full extent of the groundwater resources in the southern Perth Basin, between Bunbury and Augusta, has gradually become known through systematic groundwater investigation drilling since 1966. Significant groundwater resources have been identified and estimates have been included in reviews of Western Australia's groundwater resources.

Figure 1.1 Groundwater Investigation Programmes



Development of groundwater in the region increased rapidly in the late 1980s and 1990s. The first groundwater management area was proclaimed at Bunbury in 1975, followed by Busselton/Capel in 1984, and the remainder of the region in the Blackwood Groundwater Area (GWA) proclaimed in 1989. Groundwater Area Management Plans were completed for Bunbury and Busselton/Capel GWAs in 1994/5, but have yet to be completed for Blackwood GWA.

Following a record low runoff year in 2001 to the surface water reservoirs serving the Integrated Water Supply Scheme (which supplies water to the Perth region, the Agricultural Area and the Eastern Goldfields), the Water Corporation commenced evaluating additional water sources, including desalination, groundwater from the Yarragadee aquifer, and water efficiency measures.

The Water Corporation made an application for a 45GL/annum allocation from the Yarragadee aquifer within the Blackwood Groundwater Management Area, which was subsequently amended to include abstraction from the Busselton - Capel Groundwater Management Area. To allow consideration of the application, the Water and Rivers Commission and Water Corporation signed a formal agreement in 2002 to accelerate water management planning for the Blackwood Groundwater Management Area and the review of the existing Busselton/Capel and Bunbury GMAs.

An integral component of this is the further investigation of the Yarragadee and adjacent aquifers to determine the likely impacts of a major borefield and including the development of a three-dimensional regional scale numerical groundwater flow model of the southern Perth Basin.

This study is one of the largest groundwater investigations carried out in Western Australia, consisting of a suite of geophysical surveys, exploratory drilling at more than 60 sites (mostly within State Forest, Fig. 1.1), test pumping, evaluation of groundwater recharge and discharge, and modelling of recharge, stream flow, groundwater flow and response to pumping. Concurrent with the hydrogeological investigations, studies on groundwater dependent ecosystems and the economics of water demand were carried out.

The Scoping Report of the South-West Yarragadee Water development Project has been approved by the Environmental Protection Authority (EPA) after a four week public comment period. This report presents the Scope of Work that needs to be covered by the Water Corporation in preparing a Sustainability Evaluation and Environmental Review and Management Plan. Submittal of these plans to the EPA and the Government's Sustainability Panel are scheduled for October 2005.

2 PEER REVIEW PANEL

The Water and Rivers Commission (WRC) now DoE, appointed an expert panel to Peer Review the conceptual and numerical flow models of the South-West Yarragadee Aquifer SWAMS Version 1.2.1 (v 1.2.1) on 25 June 2003. The Peer Review Panel comprised Paul Whincup, Phil Wharton and Dr Richard Martin.

In August 2005 the Water Corporation reconvened the Panel to conduct a similar review of the updated model SWAMS Version 2.0 (v 2.0).

Paul Whincup is the nominated Chairman of the Peer Review Panel. He is a hydrogeologist with over 40 years of international experience in more than 30 countries. He is a former President of the Australian Chapter of the International Association of Hydrogeologists, a former President of the Australian Drilling Industry Association and a former Director of the Australian Drilling Industry Training Committee. He has served on the Editorial Board of International Hydrogeology Journals. He is currently the Technical Director for Environmental Resources Management (ERM) in Asia Pacific. Mr Whincup has no other involvement with the South-West Yarragadee Aquifer Project or as a consultant to Water Corporation outside this role as Chairman of the Peer Review Panel.

Phil Wharton is a Principal Hydrogeologist and Director of Rockwater Pty Ltd with over 30 years experience in Australia and other countries. Rockwater Pty Ltd is on the Water Corporation's Hydrogeological Advisory Services Panel, and carries out projects for the Corporation under that contract. Rockwater has assisted the Water Corporation with further development of the SWAMS conceptual model. Rockwater is also the hydrogeological consultant to Aqwest (Bunbury) and Busselton Water Board both of which abstract groundwater from the Yarragadee aquifer for municipal water supply.

Dr Richard Martin has had over 30 years experience as a hydrogeological consultant working in Australia, Africa, Middle East and Asia. He has worked on a multitude of water supply projects in a variety of sectors, including industrial, municipal, mining and agricultural. Dr Martin was managing director of a large private consulting company for over 15 years before being seconded into an integrated nickel mining group to provide operational management and water supply planning. Presently Dr Martin is employed by RioTinto Technical services as a Principal Consultant in Water Management. During the previous DoE Peer Review Panel assignment he was the nominated representative of the five South-West Shires which may be impacted by the withdrawal of groundwater from the Yarragadee aquifer. There is no conflict between his role as a member of the Peer Review Panel and his position with RioTinto.

3 PEER REVIEW PROCESS

3.1 PEER REVIEW BRIEF FROM WATER CORPORATION

The Peer Review Panel Brief from the Water Corporation is in line with that given by DoE in the prior review and which is attached as *Annex A*. It outlines the Scope of Work and anticipated outcomes of the Peer Review Process. Water Corporation has added an additional objective (fifth bullet point below) to the original DoE brief.

In summary the required outcomes of the Review are fivefold:

- a comprehensive assessment of the confidence, sensitivity and uncertainty of the model;
- identify aspects that can be improved;
- enhance the confidence of the model in decision making processes;
- endorse the use of the model in meeting some or all of the model objectives; and
- comment on how the updated model version (SWAMS v 2.0) has addressed any uncertainties from the previous version (SWAMS v 1.2.1).

3.2 BASIS

The Murray Darling Basin Committee (MBDC) has developed a National Groundwater Modelling Guideline which has been accepted by relevant Federal and State Government Agencies (MBDC, 2002). This Guideline provides a checklist for Peer Review of High Fidelity Models and the Panel has followed the outline of the recommended process, with modification, by adopting the key review parameters outlined by MBDC.

3.3 SCHEDULE

The Peer Review Panel was appointed by Water Corporation on 1 August 2005 and requested to finalise the review by end of September 2005. The Panel provided an Executive Summary of its findings on Sunday, 4 September 2005.

3.4 *PRESENTATIONS AND MEETINGS*

The Panel has met with Water Corporation officers five times during the course of this review and separately on four other occasions. The meetings with Water Corporation included presentations on the conceptual and numerical models and responses to formal written questions submitted by the Panel.

3.5 *REPORTS REVIEWED*

A full listing of reports presented to the Peer Review Panel is attached under 'References'. The eighteen Figures incorporated into this report are derived from these reports, specifically the Water Corporation reports on the hydrogeological investigation and on the construction, calibration and application of the SWAMS v 2.0 model.

4 ACTIONS ON PEER REVIEW RECOMMENDATIONS FOR SWAMS V 1.2.1

The Panel previously examined SWAMS v 1.2.1 on behalf of DoE and concluded that there were several areas of uncertainty in both the conceptual and numerical models which should be addressed. These uncertainties, the Water Corporation response in respect to the actions taken for upgrading to SWAMS v 2.0, and additional comments by the Panel are presented below.

4.1 CONCEPTUAL MODEL ACTIONS

The Panel had suggested that there was a deficiency in the western and southern margins of the Blackwood GWA, with little or no information collected in these regions to accurately identify the lithology and the more complex geological interactions between aquifer boundaries.

Gravity survey and analysis has been undertaken by Geological Survey of Western Australia to evaluate faulting along the western boundary of the Bunbury Trough.

Further geological and hydrogeological evaluation of existing bore data upon the Vasse Shelf was performed and incorporated into the regional mapping.

Bores (total of 11 piezometers between 6 m and 375 m depth) were drilled in the Reedia wetlands with a deep bore drilled into the Lesueur Sandstone north of the Blackwood River.

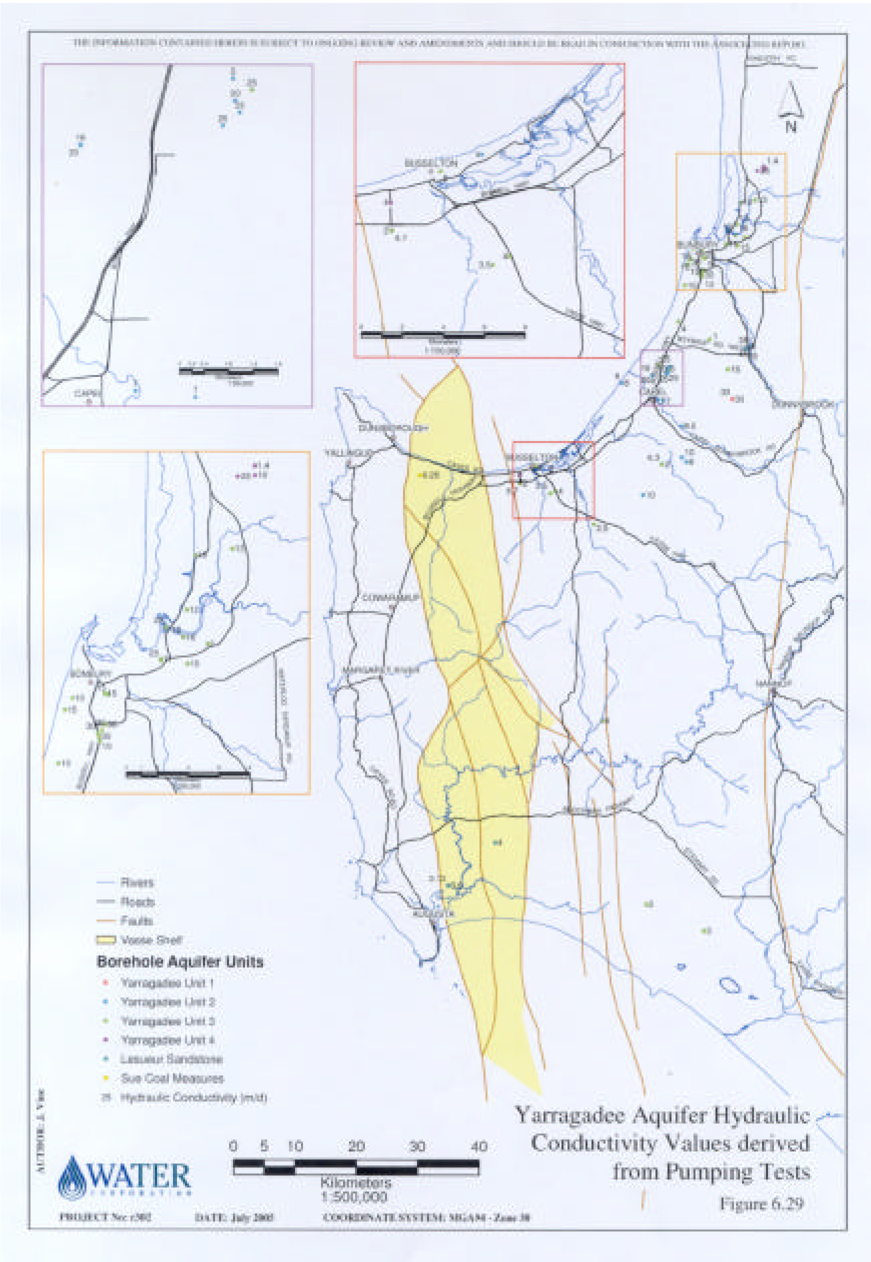
The Panel had suggested that a series of laboratory determinations of permeability and grain size analyses could provide a more quantitative measure for assigning permeability where test pumping has not been carried out.

The Panel notes that vertical permeability testing was undertaken on core samples from the bores drilled at St Johns Brook (one from Mowen, one from Leederville and two from Juy1), Poison Gully (total of four) and Reedia (total of two). Also that moisture content (equivalent to total porosity) of the St Johns Brook cores was measured. These returned 47% moisture content for the Mowen aquitard, 51% for a clayey layer within the Vasse member of the Leederville aquifer and between 22% and 26% for the Yarragadee aquifer (Juy 1).

The Panel stated that intrinsic aquifer properties had been estimated based on test pumping at one location and was considered to be a major deficiency in estimation of regional aquifer properties. It was considered essential that a list of the proposed values of hydraulic conductivity, storability, specific yield and leakage coefficients that apply to the model be tabulated and an explanation provided as to where or how these data were derived.

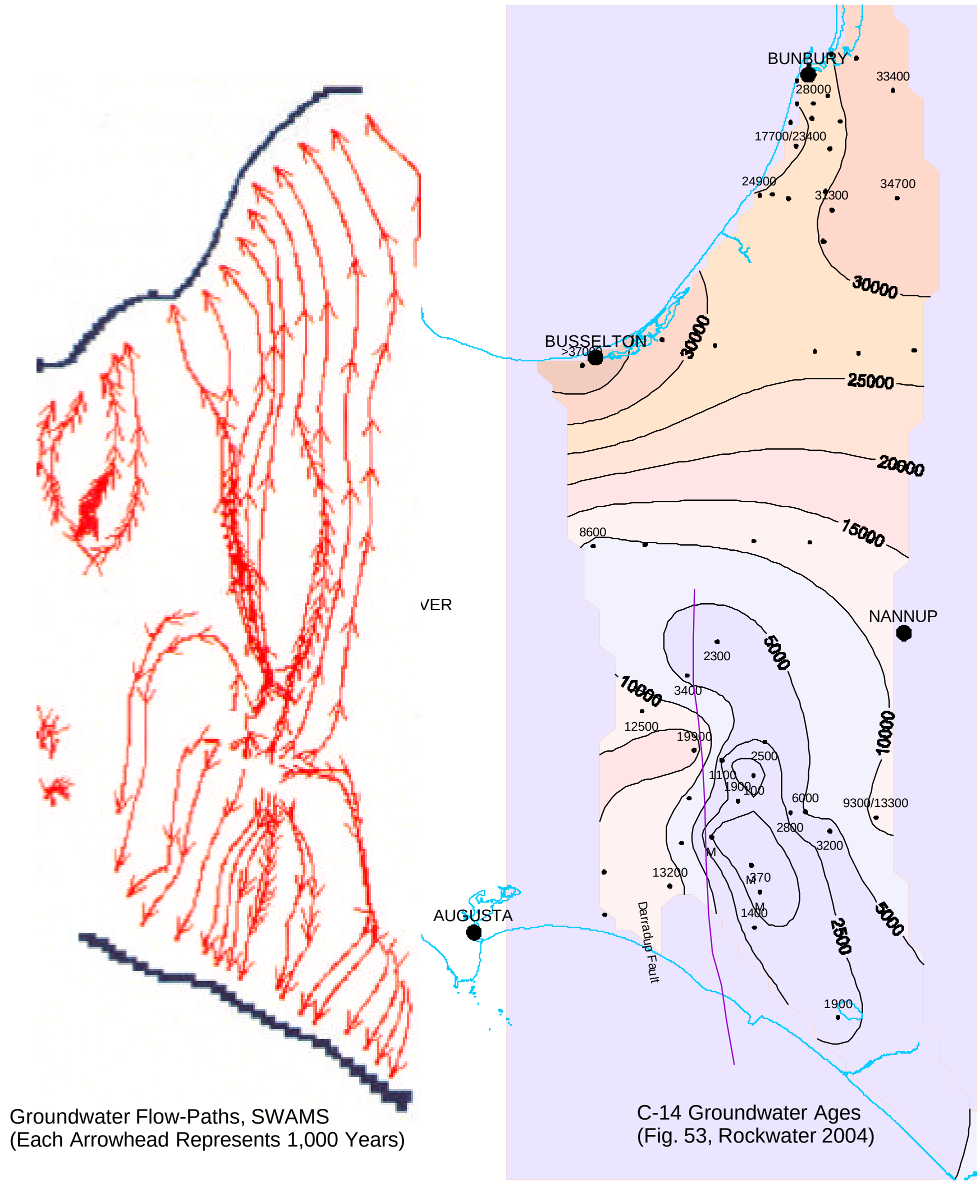
Water Corporation has provided pumping test values of hydraulic conductivities for private bores and parameter range (vertical and horizontal conductivity) have been provided for each parameter zonation for the model calibration. The Panel notes that *a total of 34 private bore pumping test data was evaluated for the Leederville aquifer and 63 from the Yarragadee aquifer (Figure 4.1). The majority of private bores in the Yarragadee aquifer are on the Swan Coastal Plain with a few on the Scott Coastal Plain. The test bore at Rosa Brook at the site of the proposed Western Borefield was tested at 10 ML/day for two weeks and drawdowns observed in a number of observation bores. The Panel has examined the pumping test data and notes that drawdowns were recorded from observation bores extending through the Yarragadee aquifer (with the exception of BP 16B, 2.5 km to the east) and into the lower third of the Leederville aquifer indicating a high vertical hydraulic conductivity. The Panel concludes that this confirms the potential for leakage not only from all units of the Yarragadee aquifer but also from the Leederville aquifer during large scale abstraction.*

Figure 4.1 Pumping Tests in Yarragadee



The Panel further notes that a series of carbon-14 age datings were measured for the Leederville (15 measurements) and Yarragadee aquifers (36 measurements) with groundwater ages in the deeper part of the Yarragadee aquifer in the northern part of the model exceeding 20,000 years. These age datings allow an evaluation of horizontal permeabilities within the aquifers by calculation of travel times based on hydraulic gradient and porosity. The Panel agrees that for the Yarragadee aquifer this equates to a regional hydraulic conductivity of 5.3 m/day between the recharge area (at monitoring bore KL 5) and the Dalyellup bore near Bunbury. Similarly software within SWAMS v 2.0 has been used to back-track Yarragadee aquifer flow lines from the Bunbury coastal discharge area to the Blackwood recharge area. The Panel compares the simulated flow paths against the carbon-14 age datings as presented in Figure 4.2 and conclude there is a reasonable agreement thereby giving credence to the hydraulic parameters adopted within SWAMS v 2.0.

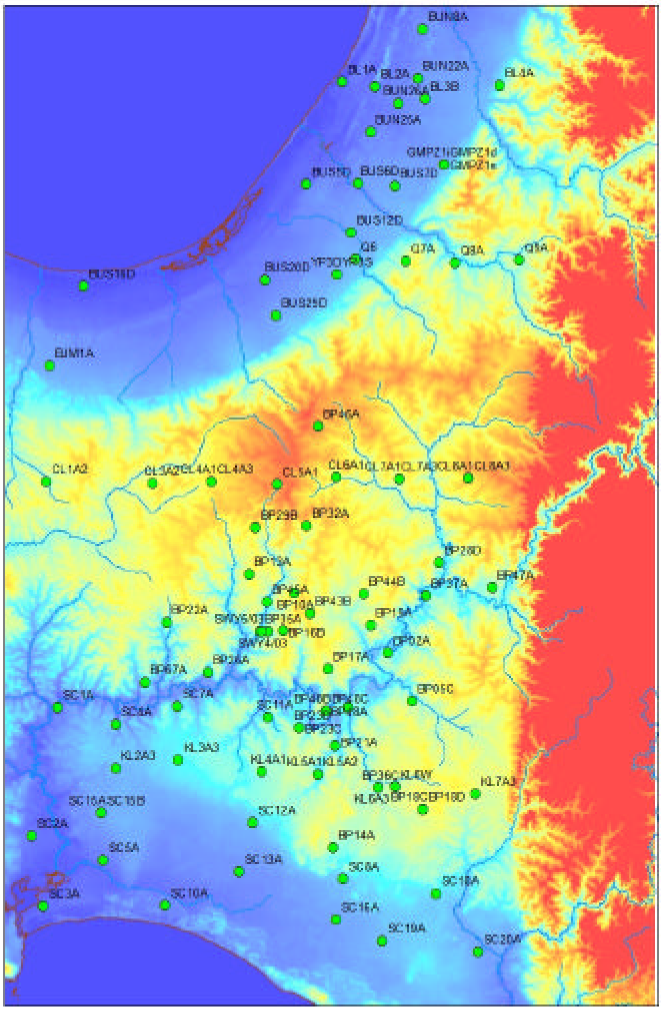
Figure 4.2 Comparison of Measured and Modelled Age Determinations for Yarragadee



The Panel had indicated that some historical water level data was erroneous due to internal leakage within the observation bores and it was recommended that a hydrogeologist should review the available monitoring data and select representative sets of bores for each aquifer for model calibration.

This was undertaken. The Panel notes that a total of 328 observation bores were determined to be returning representative water level data suitable for inclusion in the model calibration (Figure 4.3). Of these 141 are in the Yarragadee aquifer and 100 from the Leederville aquifer. Nine bores from SWAMS v 1.2.1 were excluded from SWAMS v 2.0 by reason of false non-representative values (total of three) and several shallow bores (total of six) which went dry during model calibration. The Panel has in fact reviewed hydrographs for piezometers on the Karridale (KL) and Cowaramup (CL) Lines and noted several anomalies such as bores KL7W and CL8A3 suggesting that further review should be undertaken as it is considered that there are a number of additional monitor bores which could be excluded from the calibration process.

Figure 4.3 Monitoring Bore Locations for Yarragadee



The Panel commented that the Leaf Area Index (LAI) could be greater in the South West and this would imply a much reduced recharge potential.

Response from Water Corporation is that poor soil conditions on the Blackwood Plateau is the likely cause for the lower LAI. The Panel notes that in effect LAI has not been applied in the SWAMS v 2.0 recharge estimation.

Recommended recharge values were based on initial judgement rather than those generated by WAVES and WEC-C.

Response is that WAVES and WEC-C values represent excess water that includes surface flow. Hence groundwater recharge rates should be significantly lower except over the Yarragadee outcrop where there is very little runoff. In addition surface water balance models normally give an overall magnitude of recharge and its distribution which needs to be treated as partly unknown in the groundwater model. The Panel acknowledges that four separate models have been used for comparison against recharge data generated by SWAMS v 2.0 namely WAVES, WEC-C, WATBAL which are water balance models and a chloride balance calculation. The groundwater modelling from SWAMS v 2.0 estimated recharge at 374 GL/annum whereas the other four models returned 330 (WEC-C), 360 (WAVES), 341 (WATBAL) and between 302 and 342 GL/annum (chloride balance). The Panel concludes that these various recharge estimates support the SWAMS v 2.0 groundwater modelling estimate of net recharge into the aquifer system i.e. a combination of superficial, Leederville and Yarragadee aquifers.

The results of the pumping test on bore SWY1/03 in the Western Borefield area had not been provided but returned an average hydraulic conductivity (Kh) of 6 m/day which the Panel thought was low.

Water Corporation responds that the pumping test data from private bores is consistent with the SWY1/03 findings and with modelling results i.e. lower hydraulic conductivity in the west (generally 5 to 10 m/day) and higher K (up to 30 m/day) in the east.

An explanation for the potential for leakage from the more saline overlying Leederville aquifer system was requested in terms of potential water quality changes in the underlying Yarragadee aquifer during production pumping. Also additional clarification on the bulk water chemistry was requested.

Water Corporation has conducted a detailed hydrogeochemical evaluation and the report has been made available to the Panel (included in List of References).

The Panel review of this report concurs that the major part of recharge to the Yarragadee aquifer occurs outside the outcrop area and derives by downward leakage from the Leederville aquifer and superficial aquifers on the Swan Coastal Plain as well as around Lake Jasper on the Scott Coastal Plain. Beneath the Yarragadee outcrop area the groundwater salinity is about 200 mg/L increasing to about 360 mg/L average in Juy 1 to 3 and averaging 440 mg/L in Juy4. The groundwater salinity is normally higher (typically 300 to 500 mg/L) where it is overlain by the Leederville *aquifer implying leakage from the more saline Leederville aquifer. In this situation the shallower units of the Yarragadee aquifer, where recharged from the Leederville aquifer, contain higher salinity (and higher iron content) groundwater than the deeper units. Similarly higher groundwater salinities are recorded in the shallower Yarragadee aquifer beneath the Swan Coastal Plain near Busselton and Capel, corresponding to higher salinities in the overlying Leederville and superficial aquifers. Near Bunbury a salt water wedge extends several hundred metres inland from its subcrop area beneath the superficial aquifer on the ocean floor.*

The Panel did not specifically request for additional refinement of the estimates of abstraction given in SWAMS v 1.2.1 but the Water Corporation has completed an additional evaluation of abstraction based on measured and licensed abstraction rates.

The Panel considers this exercise well justified. Water Corporation, private utilities, mining companies and other large users in excess of 0.5 GL annually are required to report abstractions, as volumes, for their operating bores. The licensed abstraction by private users refers to annual allocations of 1,500 KL or more and specifies the volume of water that may be extracted via specified bores annually – this has been converted to an average monthly figure for the model although it is recognized that this water usage has seasonal variability. Unlicensed abstraction is permitted from bores using less than 1,500 KL annually, is mainly from the superficial aquifers and has been considered to be negligible in the model.

There are 184 large capacity bores within the model area accounting for approximately two-thirds of total abstraction while the remaining 2,982 bores account for the remainder.

4.2 NUMERICAL MODEL ACTIONS

The Panel had suggested the use of the Modflow river package rather than the Drain package used in SWAMS v 1.2.1 to better represent river flows.

Water Corporation has responded that due to the complexity of the aquifer system, simple physical processes are chosen in favour of more complex ones, and the use of Drain has been continued into SWAMS v 2.0. Nevertheless it is agreed that the Modflow River package can be trialed in future development of the SWAMS model. This would allow simulation of flows from rivers back into the aquifer in locations and situations where groundwater levels are drawn down below river levels.

The Panel had questioned that direct recharge to the Yarragadee outcrop area is less than indirect recharge through the Leederville aquifer.

This is agreed by Water Corporation and is considered to be related to the much larger indirect recharge areas compared to the outcrop areas. However the low salinity of water in the Yarragadee aquifer and young groundwater ages suggest that *significant recharge does occur from infiltration of rainfall and runoff in outcrop areas.*

No verification of SWAMS v 1.2.1 was undertaken.

Verification of SWAMS v 2.0 has been undertaken by comparing model output derived groundwater ages with measured carbon-14 age datings. Also by confirming the SWY1/03 pumping test results with modelled output. In both cases model results agreed with measured data. The Panel concludes that although the model indicates flow rates are similar to those derived from age dating, it cannot allow for increases in age in the Yarragadee aquifer caused by mixing with older water from the Leederville aquifer. The Panel reinforces its view that verification of the model will need to be carried out once the aquifer is stressed and water-level and abstraction monitoring data are available for a number of years.

No model output results were presented in SWAMS v 1.2.1.

For SWAMS v 2.0 predictions of drawdowns related to a range of abstraction scenarios have been presented.

The Panel had recommended that the model include sensitivity to variable recharge.

This has been undertaken for SWAMS v 2.0.

The Panel had indicated that that uncertainty analysis was not undertaken for SWAM v 1.2.1.

In SWAMS V 2.0 uncertainty analyses have been completed for specific areas based on interpretation of local hydrogeology and water balance but it is conceded that it is difficult to do quantitatively. Uncertainty analysis should be undertaken if the SWAMS v2.0, or a local model derived from the main regional model, is to be used for assessing the impact of abstraction on groundwater dependent ecosystems.

It was recommended that drawings of model errors be presented.

This has been done for SWAMS v 2.0 with plans given for model errors for each layer in the model. As each layer can include a number of aquifers and aquitards, the Panel would like to see plans showing calibration error for each of the Leederville and Yarragadee aquifers.

The Panel had indicated that there were a number of Blackwood Plateau (BP) bores with no data in the calibration period.

The response is that there are now more bores which are used for calibration but have no data in the calibration period and these have been included as a spreadsheet in the report on the SWAMS v 2.0 numerical model. The Panel view is that it would be useful to present hydrographs for the more-recent bores that show model-calculated water levels, and measured water levels even though those levels were measured outside of the calibration period.

The Panel had indicated that in SWAMS v 1.2.1 the calibrated heads near the Blackwood River did not match observed readings.

The Water Corporation responds that in SWAMS v 2.0 the heads near the Blackwood River now match closely and drain discharge coincides with river flows in the Yarragadee outcrop area. River flows in the zone of Yarragadee outcrop along the river are similar to model calculated flows. Head errors for Layer 7 range from -7 m to +6 m near the river, and are generally less than 2 m.

The Panel had pointed out that seasonal water level variation did not fit well with observed readings.

In SWAMS v 2.0 a runoff rather than rainfall time series has been used to scale recharge time series and this has significantly improved simulation. The magnitude of seasonal fluctuations for the calibration hydrographs is generally less than observed.

The Panel had reported that SWAMS v 1.2.1 could not be used for sustainable yield determination and this is listed as one of the objectives of the model in the Peer Review Panel brief.

Water Corporation responds that there needs to be a well recognised quantitative definition for sustainable yield before it can be estimated. The Panel agrees with this comment as sustainable yield must take into account environmental, social and economic impacts which are difficult to combine into a numerical model.

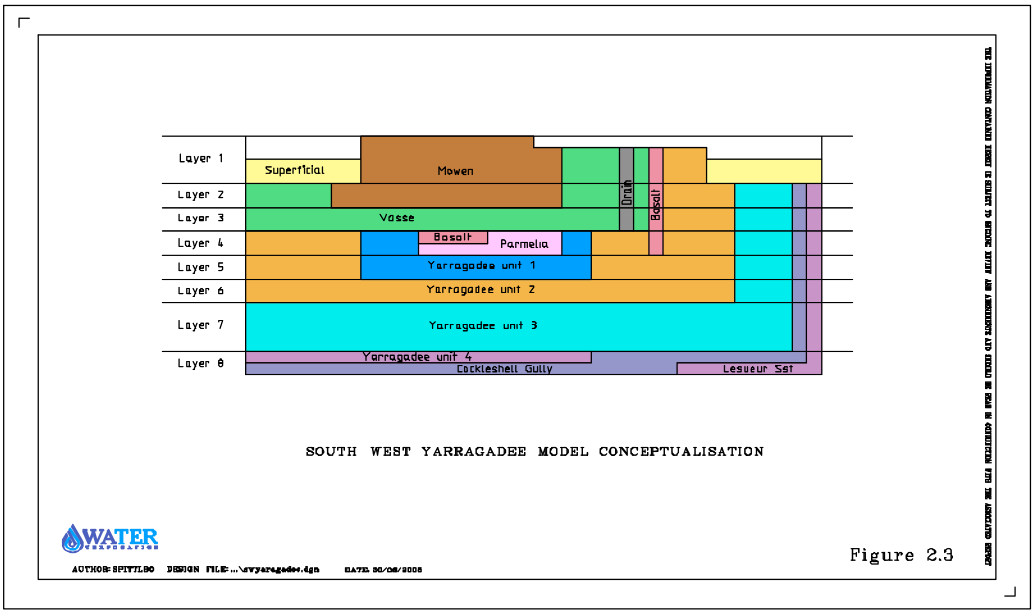
During the review of SWAMS v 1.2.1 the modelling of seawater intrusion risk was raised.

Some tentative analysis has been undertaken in SWAMS v 2.0 acknowledging that without any data this is difficult to assess. Boundary conditions have been revamped in SWAMS v 2.0 and environmental heads set up for submerged ocean areas. The Water Corporation attests that the model can be used to estimate water levels and drawdowns at the coast arising from the planned abstraction, and these values can be used to judge whether there will be a risk of seawater intrusion.

5 THE SWAMS V 2.0 CONCEPTUAL MODEL

Conceptualisation of groundwater flow systems is required for its representation in a numerical groundwater model. Aquifers and aquitards of the southern Perth Basin have been simplified into hydrogeological units that can be fundamentally described in model layers. The conceptual model divides the aquifers into eight layers (*Figure 5.1*).

Figure 5.1 Conceptual Model



There are three broad levels of groundwater flow systems within the southern Perth Basin. They are the superficial aquifer, Leederville aquifer, and Yarragadee aquifer. The Lesueur Sandstone upon the Vasse Shelf is treated as a separate aquifer system hydraulically connected with the Yarragadee aquifer. The superficial aquifer is present within the Quaternary sediments upon the coastal plains, but can also include shallow groundwater flow within colluvium and weathered profile upon the Blackwood Plateau. The Leederville aquifer comprises the Vasse Member of the Leederville Formation, including the Leederville sand unit that occurs in parts of the basin (2B), and the upper sand member of the Parmelia Formation where it is present (3A). The Yarragadee aquifer is a major regional aquifer that incorporates several formations, but is dominated by the Yarragadee Formation. The Yarragadee aquifer is defined as that part containing water with salinity less than 1000 mg/L TDS.

Due to the large thickness and complexity of the Yarragadee flow system the aquifer is sub-divided into several units representing the different formations and lithologies that make up the aquifer. The Yarragadee aquifer contains four defined units. Yarragadee 3 (Juy3) is the most transmissive portion of the aquifer and should be represented as an individual model layer, while the distribution and lithology of Yarragadee units 1 (Juy1) and 2 (Juy2) are sufficiently similar to allow them to be represented as a single layer (they were treated separately in previous version). Yarragadee 4 (Juy4), situated at the base of the formation, is not always present, and can be treated as a separate unit or grouped with the underlying Cockleshell Gully Formation.

Other formations that make up the Yarragadee aquifer are the Cockleshell Gully Formation and Lesueur Sandstone within the Bunbury Trough. The aquifer includes the upper-most portion of the Cockleshell Gully Formation through much of the basin, but it is only in the southern part of the basin that the Lesueur Sandstone forms part of the aquifer. The Cockleshell Gully Formation and Lesueur Sandstone are treated as a single hydrogeological layer due to their position at the base of the aquifer and generally good hydraulic connection.

The major aquifer units are separated by two aquitard units. The Mowen aquitard separates the superficial aquifers from the Leederville aquifer and the Parmelia aquitard separates the Leederville and Yarragadee aquifers. The Mowen aquitard allows minor leakage through the unit driven by large downward hydraulic head gradients that exist below the Blackwood Plateau. Where the Mowen aquitard is absent, the superficial aquifer may be in hydraulic connection with the underlying Leederville aquifer, and this may occur over much of the Swan and Scott Coastal Plains. The Leederville aquifer outcrops upon the Blackwood Plateau where the Mowen aquitard is absent. North of the Capel River the Mowen “aquitard” is predominantly sand and effectively forms part of the Leederville aquifer.

The Parmelia aquitard separates the Leederville and Yarragadee aquifers through much of the eastern part of the basin. It comprises the clay unit of the Parmelia Formation and the Bunbury Basalt. The Bunbury Basalt is considered to be an almost total barrier to groundwater flow, while the Parmelia aquitard has a very low vertical permeability except about the margins of its distribution where more leakage may be possible. The Leederville and Yarragadee aquifers are hydraulically connected where the Parmelia aquitard is absent, although interbedded clays of the Leederville may restrict the degree of connection.

Groundwater is recharged by rainfall after evapotranspiration losses. A large proportion of recharge is lost by evapotranspiration in areas where the water table is within rooting depth of the vegetation. Some streams draining the Blackwood Plateau may contribute to recharge via downward leakage, especially Rosa Brook, Milyeannup Brook, and possibly part of Margaret River. The superficial aquifer is recharged upon the coastal plains, but a large portion is lost through drainage. The Leederville aquifer is mostly recharged upon the Blackwood Plateau where the aquifer outcrops, but there may be important recharge about the inland margins of the coastal plains where it is hydraulically connected with the superficial aquifer in areas having downward head gradients. The Yarragadee aquifer is recharged directly by rainfall where it outcrops, but downward leakage via the

Leederville aquifer and superficial aquifer may be a more important source due to the much greater surface areas. Rates of recharge via downward leakage through the Mowen aquitard upon the Blackwood Plateau are considered to be low.

Rainfall data used in SWAMS v 2.0 are annual averages for the period 1980 to 2003 (*Figure 5.2*), which is a period of reduced rainfall compared to available records for Perth extending back to 1876 (*Figure 5.3*). Global warming is predicted to result in reducing rainfalls over the next decades and the impact of reduced rainfalls on recharge needs to be modelled. There is, however, no certainty that rainfalls will decline.

Figure 5.2 South West Rainfall and Evaporation 1980-2002

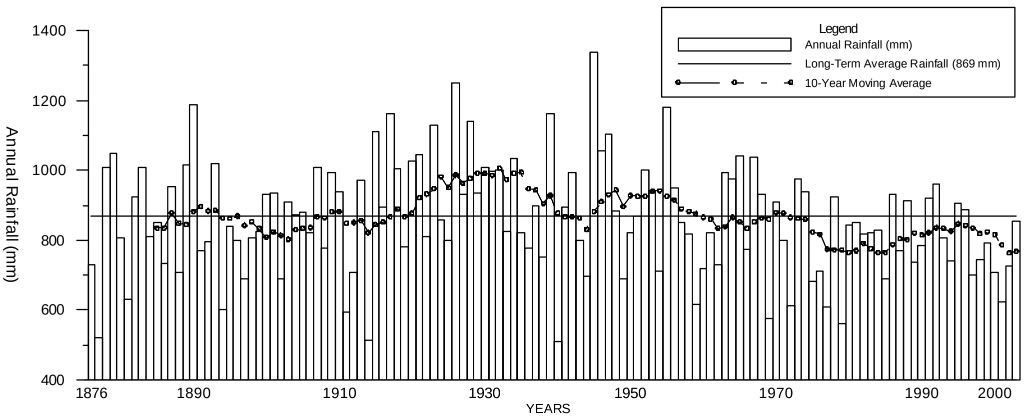
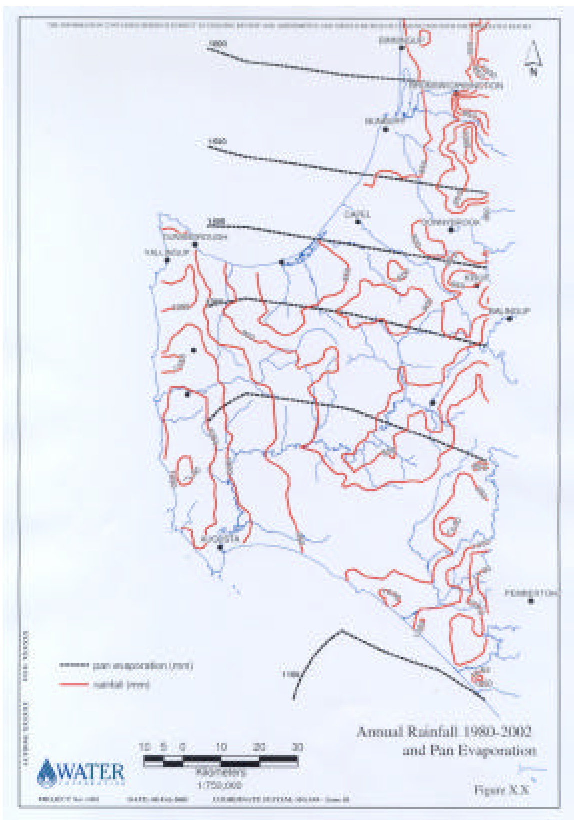


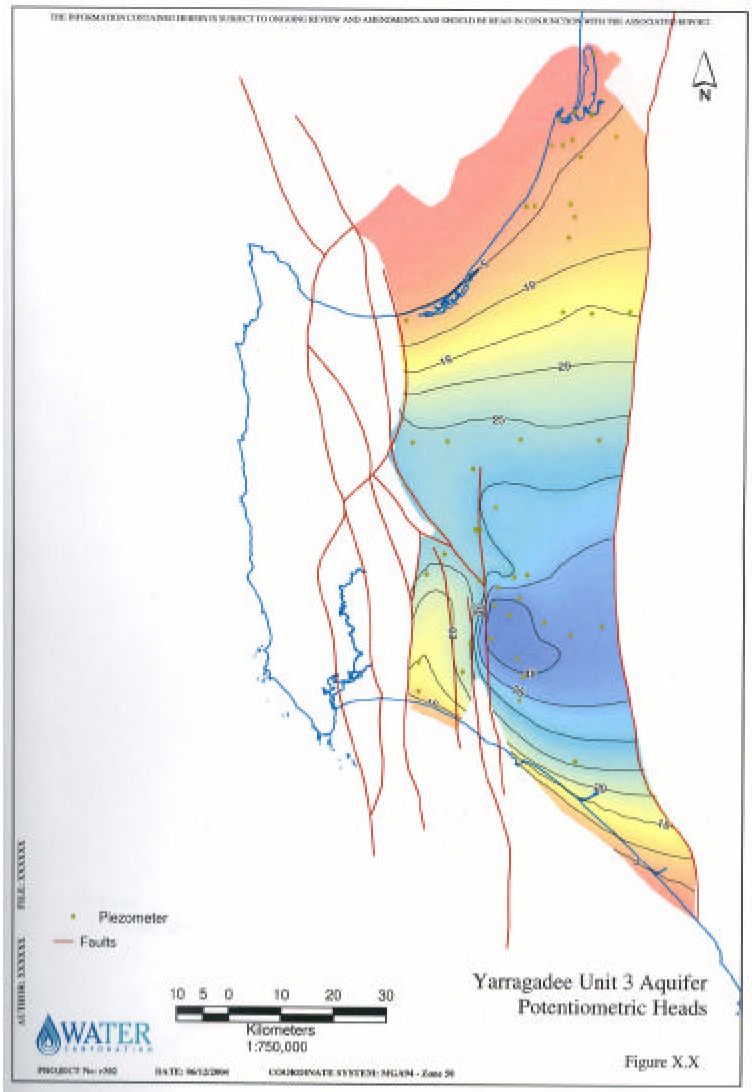
Figure 5.3 Perth Rainfall 1876-2003



Groundwater flow within each of the hydraulic units is controlled by the lithological properties. Faulting is considered to have some effect on flow, with flow restricted across faulted contacts (in the Yarragadee and Lesueur Sandstone aquifers). The flow systems are bounded to the east and west by impermeable crystalline basement of the Yilgarn Craton and Leeuwin Block respectively. Interbedded clays within the aquifers impede the vertical movement of groundwater, but do not act as extensive aquitards.

The aquifers are open to the ocean to the north and south, where upward flow and diffuse discharge occurs. Areas of concentrated discharge from the Yarragadee aquifer occur adjacent to Bunbury in the north and Black Point in the south. Significant discharge also occurs into the Blackwood River and to a lesser degree the Donnelly River, where they intersect the aquifers. The pattern of groundwater flow in the Yarragadee aquifer (Juy3) is shown by the head contours in *Figure 5.4*. The potentiometric head is highest near the outcrop / recharge area at 45 m above sea level. Flow from the recharge area is southwards to the Southern Ocean and northwards to the Indian Ocean.

Figure 5.4 Potentiometric Heads in Yarragadee



6 PEER REVIEW OF SWAMS V 2.0 NUMERICAL MODEL

6.1 MODEL DESCRIPTION

Modifications made to the SWAMS v 1.2.1 model in establishing version 2.0 included the following:

- Modification of geology, layering, faults and boundary conditions
- Use of environmental heads to represent ocean boundaries
- Use of the Drain software package to represent all major rivers
- New zonations for parameters and recharge
- New time-series scaling factors for abstraction and recharge
- Introduction of horizontal anisotropy, and
- Representation of evapotranspiration on the coastal plains.

The updated SWAMS v 2.0 is a considerable improvement of SWAMS v1.2.1.

The model domain for SWAMS v 2.0 is 190 km long by 70 km wide and covers an active area of 8,500 km^2 of which some 6,000 km^2 is onshore. The Yarragadee occupies 7,260 km^2 of the model area of which 4,885 km^2 is onshore and has a maximum thickness of up to 1,700 m. The model has eight layers

6.2 REVIEW METHOD

The major headings from the checklist in the National Groundwater Modelling Guideline developed by the MDBC were used as the basis for this review of the numerical modelling by the Water Corporation (August 2005). The results of the review, in particular any possible shortcomings in the modelling, are discussed under each heading below.

6.3 DATA ANALYSIS

A comprehensive set of drillhole, geological, hydrogeological, water chemistry, stream-flow, climatic and groundwater abstraction data were collected and analysed for the modelling. These data are largely from the area of the planned borefield, and from areas of existing groundwater development such as Bunbury and Busselton.

6.3.1 Recharge

Recharge rates were initially estimated by judgement based on the hydrogeology (lithologies), and using chloride balances for shallow aquifers. They were adjusted to achieve calibration of the model, and were compared with estimates using WAVES and WEC-C recharge models, and WATBAL, a water-balance model.

The seasonal distribution of recharge was varied in SWAMS 2.0 to better match observed water-level fluctuations.

Recharge was applied to the highest active layer. There have been some problems where there are inactive cells: the underlying active cell is confined, and so recharge applied to a cell where a low storage coefficient applies caused very high hydraulic heads. Recharge was taken off these cells to overcome the problem.

Adopted recharge rates range from 5 to 350 mm per year, and generally appear to be of the correct order. Net recharge to the model for the calibration period is 374 GL/a. This is supported by estimates of 282 to 340 GL/a from the recharge and water balance models.

Recharge should not be applied in the model to areas of basalt sub-crop, as the basalt is essentially impermeable.

6.3.2 Hydraulic Conductivity

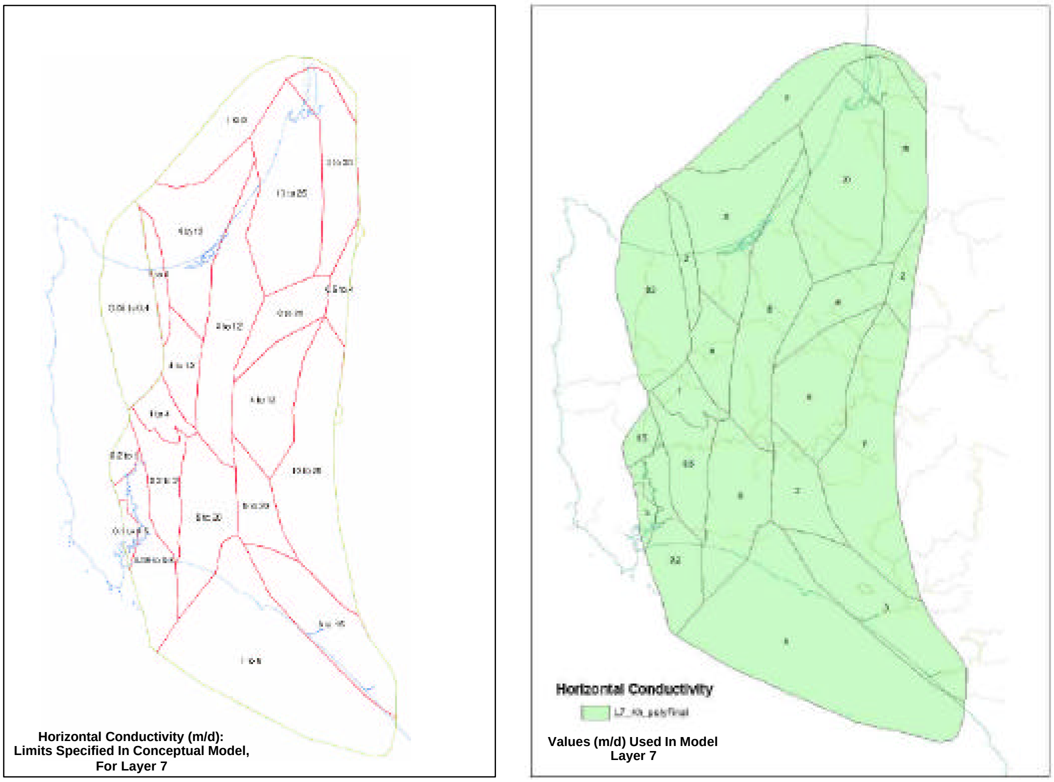
A single pumping test has been carried out for the investigation, on bore SWY 1/03 screened in the Yarragadee aquifer. Other pumping test data have also now been used, primarily for Leederville and Yarragadee bores on the Swan Coastal Plain.

The distribution of chloride concentrations and groundwater ages in Unit 3 of the Yarragadee aquifer suggest there are high rates of groundwater flow from outcrop areas, and that this flow dominates leakage to the formation via the Leederville aquifer. This indicates relatively high horizontal hydraulic conductivity for the Yarragadee aquifer.

A value of hydraulic conductivity of 25 m/day adopted for Layer 1 on the Scott Coastal Plain around Lake Jasper seems to be too high in an area of mainly clayey sediments. Similarly, a value of 10 m/day for Layer 1 on the Swan Coastal Plain appears to be high for the Guildford Formation.

Ranges of horizontal hydraulic conductivity given in the conceptual model, and values adopted in the numerical model, are shown in *Figure 6.1*.

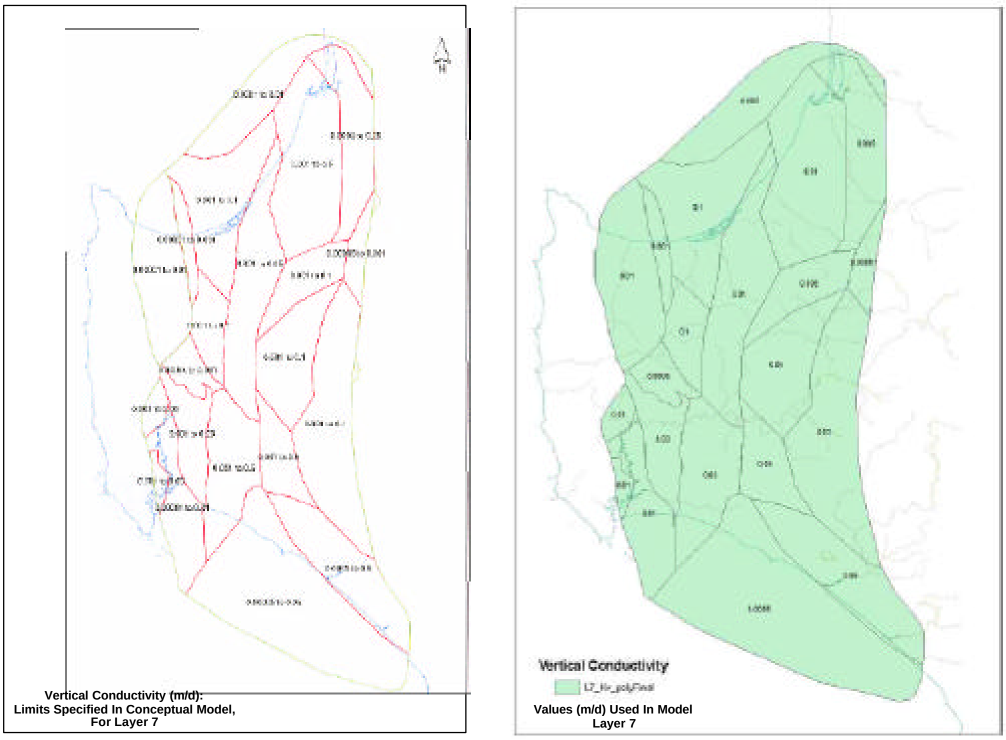
Figure 6.1 ***Conceptual and Modelled Horizontal Hydraulic Conductivities for Yarragadee Aquifer***



Vertical hydraulic conductivity values for the Leederville Formation should be less than those of the Yarragadee Formation to reflect the difference in clay/shale content, as they are in the PRAMS (Perth Regional) model. The amount of water leaking from the Leederville to the Yarragadee is a product of values for both aquifers: higher values for the Yarragadee and lower values for the Leederville than those used in the model could give the same rate of leakage.

Ranges of vertical hydraulic conductivity given in the conceptual model, and values adopted in the numerical model, are shown in *Figure 6.2*.

Figure 6.2 Conceptual and Modelled Vertical Hydraulic Conductivities in Yarragadee



6.3.3 Model Design

The model design is good and generally appropriate for its intended use. SWAMS 2.0 has been changed so that each layer has been divided into a number of zones to coincide with changes in geology and topography, and parameters have been assigned to each zone. This approach is supported.

Consideration should be given to using the Modflow River package rather than the Drain package for modelling of the Blackwood and Donnelly Rivers. This would enable flow from the rivers to the aquifers to be simulated, if necessary. The Drain package can only represent flows from aquifers to the rivers, and is satisfactory provided river levels will always remain above groundwater levels.

The model probably has more layers than were necessary to represent vertical differences in hydrogeology. This would not affect the efficacy of the model, but can make calibration more difficult.

Dry cells should be scrutinised to ensure they are not causing high calculated heads in the model. They can cause the underlying layer (the upper-most active layer) to remain confined when it should be unconfined. Recharge to the layer can then result in high, unrealistic heads because a low storage coefficient (rather than specific yield) applies.

Boundary conditions along the northern and southern coasts should be changed to reflect measured hydraulic gradients in each model layer.

6.3.4 Calibration

SWAMS v 2.0 was calibrated over the period 1990 to 2003 using 337 monitor bores and indicated some improvement when compared to SWAMS v 1.2.1. However, the difficulty in calibrating to heads in the Mowen Member and Leederville aquifer reflects the complexity of these systems compared to the Yarragadee aquifer.

Hydrographs that included erroneous monitoring data, or that were unrepresentative because of, for example, inter-aquifer leakage via bore annuli, are said to have been omitted in calibrating version 2.0 of the model. There still appear to be some bores with erroneous monitoring data being used.

The plots of observed versus calculated heads show a wide scatter, particularly at high heads for the Leederville aquifer (*Figure 6.3*). Those for the Yarragadee aquifer are shown in *Figure 6.4*.

Figure 6.3 Modelled vs. Observed Heads in Leederville

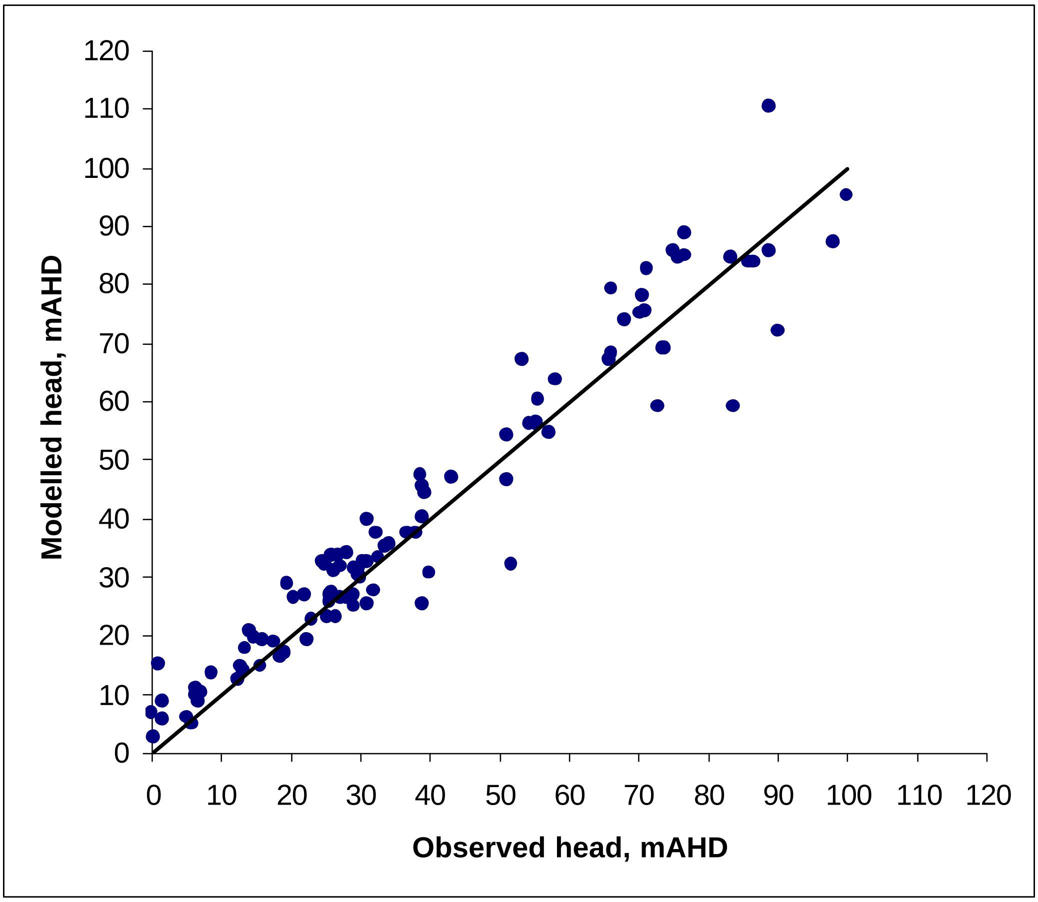
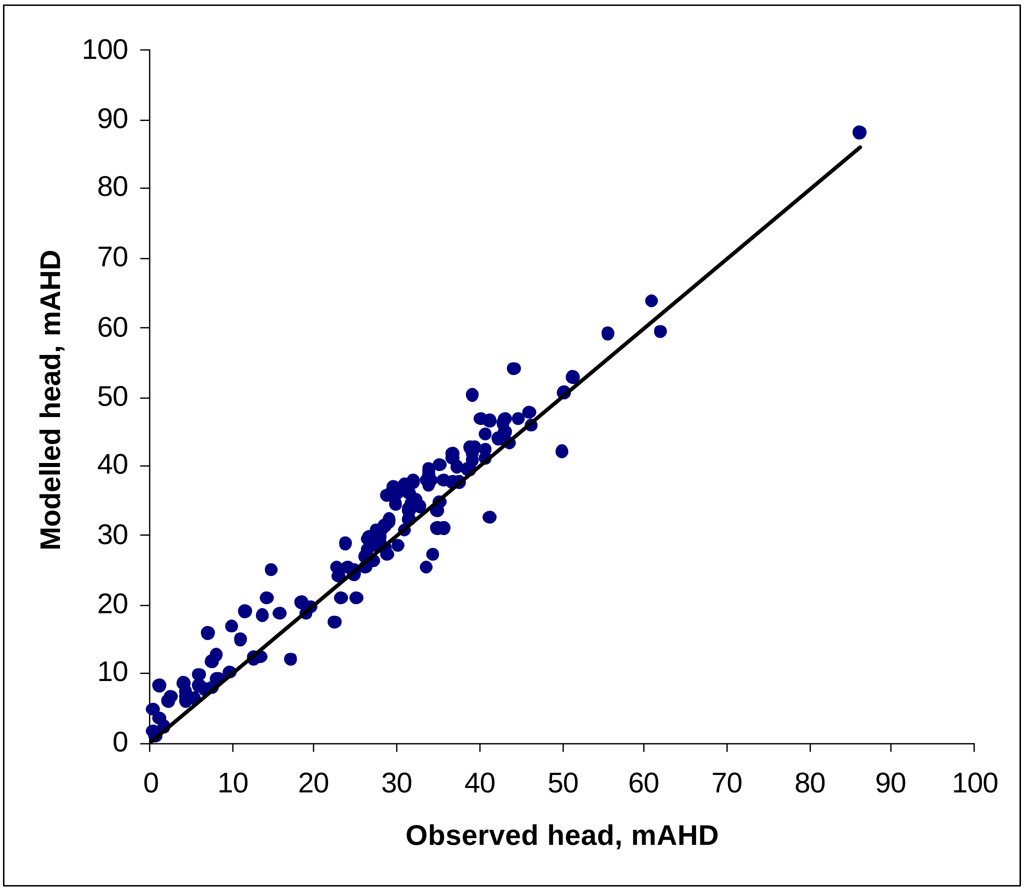


Figure 6.4 Modelled vs. Observed Heads in Yarragadee



There has been marginal improvement in error statistics compared to the SWAMS version 1.2.1, particularly considering that monitoring bores with doubtful data are no longer used in the comparison:

Aquifer	**Av. Absolute Error (m)**		**Av. RMS Error (m)**		**Max. Positive Error (m)**		**Max. Negative Error (m)**	
	Model 1.2.1	**Model 2.0**	**Model 1.2.1**	**Model 2.0**	**Model 1.2.1**	**Model 2.0**	**Model 1.2.1**	**Model 2.0**
Superficial	1.9	0.8	2.5	2.9	6	8.4	-8.6	-7.4
Leederville	4.2	3.6	6	7	40	28	-26	-35
Yarragadee	3.2	3.1	4.5	4	36	13	-15	-9

Time-series water-level plots showing model-calculated and observed groundwater levels are presented in the modelling report for a large number of bores in the Superficial, Leederville and Yarragadee aquifers. Some of the hydrographs show a significant disparity between measured and calculated water levels, particularly for the Superficial and Leederville aquifers. Also, for many of the hydrographs, calculated seasonal fluctuations are smaller than observed fluctuations, possibly indicating that the modelled storativity is too high.

Some of the calculated water levels follow a downward-declining trend not seen in the monitoring data. For example, many of the Scott Coastal Plain superficial and Leederville bores; and some Yarragadee bores such as SC20A and KL2A3. This could result in the model over-estimating drawdowns in future pumping scenarios.

The closest correspondence between calculated and measured groundwater levels was for the Yarragadee aquifer. There was a good match in the data (< 2 m difference) for about 50 bores. Twenty-one bores had water-level differences of more than 5 m, and five were greater than 10 m.

The largest errors are for the Leederville aquifer, as would be expected with the high vertical head gradients within the formation. For example, 14 m at BP02 and 22 m at BP17 near the Blackwood River; 28 m at BUS24 on the Swan Coastal Plain; 16 to 26 m at BP20, BP33 and BP42 near Stewart Road; 12 m at CL8 and BP08 near St John Brook; 35 m at CL3 near Margaret River; and 20 m at BP13 near Rosa Brook.

The model was also calibrated to flows in the rivers. Although a satisfactory match was obtained between calculated and observed flows in the Scott River and in the Blackwood River in the Yarragadee outcrop area, there were substantial differences for the total flows to the Blackwood River between Nannup and Hutt Pool, and for the Donnelly River:

In terms of Donnelly River flows 22.2 GL/annum was modelled compared to 6 GL/annum observed. The difference cannot be explained by evapotranspiration (ET) losses from the river and fringing vegetation.

Similarly, for the Blackwood River between Nannup and Hutt Pool 59.5 GL/annum was modelled;41 GL/annum was calculated from the salt balance and 24 GL/annum was observed. The modelled value is too high and reflects an overestimate of the contribution from the upper aquifers to the Blackwood River. In future model versions, river flows should be modelled more accurately, as the rivers are of high environmental value.

We understand that the complexity of the hydrogeology, and consequently the size and complexity of the model make it unlikely that average head errors of better than 3 to 4 m can be achieved, and that it would be difficult to simulate actual river flows. This makes the model unsuitable for determining the impacts of extraction on Groundwater-Dependent Ecosystems (GDE's), where small changes in groundwater level or discharge rates can be important.

The water balance for the model indicates that net recharge to the Yarragadee aquifer (excluding discharge to rivers) comprises 120 GL/annum leakage from the overlying Leederville aquifer and 44 GL/annum from direct recharge in areas of outcrop

6.3.5 *Verification*

Verification of the model would be difficult to carry out at present because of the limited period for which monitoring data are available and also because of the limited stress that has been applied to the aquifer over much of the area (ie. total abstraction compared to groundwater recharge and throughflow).

Some verification has been made by running the flow-path model PMPATH to simulate flow directions and travel times from the main Yarragadee recharge area and comparing the travel times with groundwater ages determined by Carbon-14 dating. The indicated patterns of flow are similar for both methods. Ages (flow times) indicated by the modelling are less than the Carbon-14 ages, but this is to be expected with the mixing of older water leaking down to the Yarragadee aquifer from the Leederville Formation.

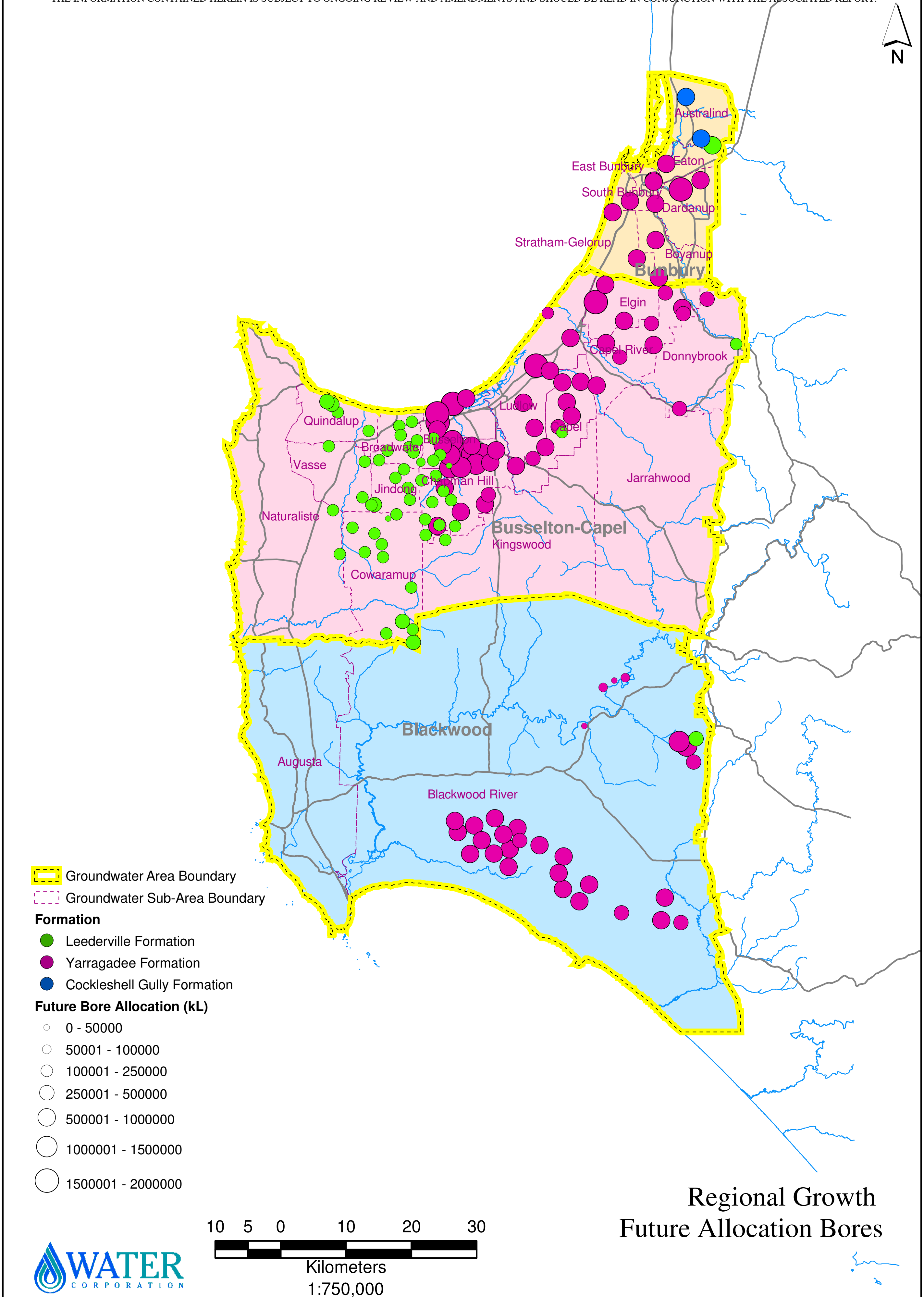
The groundwater flow model was also used to simulate the 14-day pumping test on the test-production bore SWY1/03. Horizontal hydraulic conductivity values that were needed to match the test drawdowns ranged from 9 to 10 m/d for various versions of the model, compared to 6 m/d determined from the pumping test data. These values are reasonably consistent, given that the bore did not draw water evenly from the full thickness of the aquifer.

Model verification can be carried out in the future when additional abstraction will subject the aquifers to localised stress.

6.3.6 *Predictions*

The model was run to simulate a number of abstraction scenarios over 30 years from 2004, including a continuation of 2004 abstraction; an expected increase in regional growth (private plus utility) abstraction (Fig. 6.5); and regional growth combined with the proposed 45 GL/annum Water Corporation abstraction. The projected regional growth in abstraction from the Leederville and Yarragadee aquifers is indicated on *Figure 6.5*.

THE INFORMATION CONTAINED HEREIN IS SUBJECT TO ONGOING REVIEW AND AMENDMENTS AND SHOULD BE READ IN CONJUNCTION WITH THE ASSOCIATED REPORT.



Regional Growth Future Allocation Bores

PROJECT No: r302 DATE: July 2005 COORDINATE SYSTEM: MGA94 - Zone 50

For the Water Corporation abstraction, two main scenarios were run: a Western Borefield north of the Blackwood River (bore SWY1/03), and an Eastern “Split” Borefield located east of St John Brook. Bores in the Eastern Borefield would be constructed to abstract 22.5 GL/annum equally from each of the upper (Juy1) and lower (Juy3) parts of the Yarragadee aquifer.

The modelling results indicate that the split borefield would reduce the extent of drawdowns and the impact on private users. It could, however, reduce shallow groundwater levels near, and flows in, St Johns Brook.

The scenarios run included scenarios with 5% and 10% reduction in recharge.

Of prime interest is the predicted impact on the uppermost model layer (Layer 1) after 30 years of pumping. The modelling results indicate there would be drawdowns of up to 2 m or more on the Swan and Scott Coastal Plains; and up to 5 m along and near the Blackwood River where the Yarragadee Formation outcrops. However, in this area artesian pressure in the Yarragadee will remain above the river level and the aquifer will continue to discharge to the river.

The Panel considers it very unlikely that drawdowns of this magnitude would occur at the water table, and that the model provides a degree of conservatism when predicting drawdowns for the following reasons:

1. The model does not allow for re-circulation of recharge water, or water that currently runs-off from the coastal plains rather than recharging the shallow aquifer because the aquifer is full in winter. Lowering the water table will increase recharge rates;

2. The model does not allow for the slow drainage of the large volume of groundwater stored in pores in fine-grained layers of the Leederville Formation. Porosities are higher in these layers, between 30% and 50%. The leakage will occur over a wide area and will contribute significantly to the capacity of the Yarragadee aquifer;

3. During model calibration, the calculated hydrographs for many bores show a decline in water levels from late 2000 that is not seen in the monitoring data; and

4. In areas where there were dry cells in the model at the water table, drawdowns in Layer 4 were taken to represent drawdowns at the water table. Layer 4 drawdowns would be much larger than drawdowns at the water table because of the low vertical hydraulic conductivity of the Leederville Formation.

The modelled water balance of the study area under average recharge conditions indicates a gross recharge of 632 GL/annum, which under the regional growth scenario estimates that 234 GL/annum is lost as evapotranspiration on the Swan and Scott coastal plains, and that 398

GL/annum is net recharge. SWAMS v 2.0 predicts that with the addition of 45 GL/annum abstraction from the Eastern Borefield, the evapotranspiration reduces to 227 GL/annum and net recharge increases to 405 GL/annum. Of the proposed 45 GL/annum Eastern Borefield abstraction, 13 GL is from reduced ocean outflow, 19 GL is derived from storage in the aquifer, 6 GL is from increased net recharge, and 7 GL is from reduced outflow, mostly to the Blackwood River. An evapotranspiration component for the Blackwood River needs to be incorporated into the model to justify these estimates.

6.3.7 *Sensitivity Analysis*

The sensitivity analysis has been carried out for hydraulic conductivity (vertical and horizontal), specific yield and recharge. Confined storativity (specific storage) was not included as the previous version of the model was found to be insensitive to that parameter.

The model is most sensitive to recharge. The heads in each aquifer are also sensitive to the horizontal hydraulic conductivity of the aquifer and the vertical hydraulic conductivity of the aquifer and any overlying layers.

Recharge and hydraulic conductivity (both vertical and horizontal) are interdependent. The model calibration is not unique – the model could be calibrated with the adopted recharge rates; or with a set of higher recharge rates and corresponding higher values of hydraulic conductivity.

6.3.8 *Uncertainty Analysis*

Uncertainty analysis has not been carried out, but should be if the model is to be used to predict the effects of abstraction on GDE's, and other groundwater users.

6.3.9 *The Report*

A draft report has been prepared describing construction, calibration and application of the model (Hua Sun, 2005). It is comprehensive but has probably not yet been subject to internal review. Some additions/changes should be made to:

- Include plans showing observed, and model-calculated heads from model calibration;
- Show the borefield that was simulated in the drawdown plots (eg. *Figure 6.3*); and
- Show measurement units on plans and tables.

Two other reports have also been prepared that are related to the model and modelling results:

SWAMS Groundwater Model V2.0 Conversion of conceptual model into numerical model.

South West Yarragadee Investigations, Impact Areas of Interest and Significance of Simulated Drawdown (August 2005). The purpose of this report is to provide a realistic interpretation of the results of modelling of future extraction, to take into account factors such as rejected recharge that cannot be adequately simulated in the model. The Review Panel supports this approach. Some comments/concerns arising from the report follow:

- Areas said to be non-sensitive include farm land on the Scott Coastal Plain that could have Acid Sulphate Soils, and so be very sensitive to drawdowns.

- The interpretations for drawdown around Tutunup, and Wonnerup Wetlands, suggest that drawdowns will be less than calculated because inappropriate values of horizontal or vertical hydraulic conductivity have been used in the model. Appropriate values should be used in the model.

- The report refers to the Mowen Aquitard, and the Vasse Member including the Leederville Aquifer, and yet vertical hydraulic conductivity values used in the model for the Mowen Member are similar, and in some cases higher than those for the Vasse Member. Also, similar horizontal hydraulic conductivities are used for both Members.

7 SUITABILITY OF MODEL TO MEET OBJECTIVES

The stated objectives of the modelling, *comments on each objective provided by the DoE*, **and the Panel's opinion on the suitability of model v. 2.0 to meet the objectives**, are given below.

The objectives of the SWAMS numerical groundwater model are to:

1. Simulate groundwater flow within and between all hydrogeological units in the southern Perth Basin that are within the active part of the groundwater flow system.

   Concentrating on Yarragadee; the inclusion of other aquifers is to ensure that groundwater flow in Yarragadee and leakage in or out is modelled.

   The model provides an adequate representation of groundwater flows in the Yarragadee aquifer, although there is some uncertainty in values of hydraulic conductivity adopted for the Yarragadee, and hence the balance between flows in the aquifer, leakage to the aquifer from the Leederville aquifer, and direct recharge to the Yarragadee.

2. Establish a water budget for the Yarragadee aquifer.

   The model budget is of sufficient accuracy to show that groundwater flows in the Yarragadee aquifer are much greater than the planned abstraction of 45 GL/a.

3. Provide first estimates of water budgets for other aquifers.

   For 2 and 3 above: Yarragadee should be reliable; other aquifers are best estimates.

   Water budgets for the Superficial and Leederville aquifers are estimates, which will be improved as the model is developed.

4. Under a range of scenarios, including the proposed Water Corporation abstraction of 45 GL/year from one or more possible borefield locations, predict the scale of changes in groundwater potentiometric heads/water levels within the hydrogeologic units.

   Predict the scale of changes in Yarragadee principally within the aquifer interval being pumped (JUY3), also within upper Yarragadee, and recognising that prediction of groundwater levels in units overlying Yarragadee will depend on connectivity – the better prediction in well connected units.

   The model can be used to predict water level drawdowns and the extent of drawdowns around borefields in various locations, in the section of the aquifer being pumped. The accuracy of these predictions is questionable at the stage of development of v. 2.0, particularly for

overlying units of the Yarragadee aquifer and the Leederville aquifer, but they can be considered to be conservative.

5. Evaluate likely changes in groundwater discharge to rivers (including the Blackwood River), streams and wetlands, and ocean environments.

Principally in Blackwood River which is well connected with the Yarragadee aquifer, also where possible wetlands and ocean directly connected to Yarragadee; predictions for discharge in overlying Leederville or Superficial aquifers will be less reliable.

Model v. 2.0 was not calibrated closely to heads measured in bores near the Blackwood River, and to flows in some reaches of the river. The accuracy of predictions of changes in groundwater discharge to the river will, therefore, be questionable. The relationship between the Yarragadee and the Blackwood River in the principal discharge zone is well calibrated.

6. Predict the general drawdown in water levels near other groundwater users, wetlands, and rivers and streams in the project area, and provide seasonal variations in such reductions.

Principally in the Yarragadee interval pumped and only in wetlands, rivers and streams hydraulically well connected to the Yarragadee, with less reliable prediction in areas underlain by Leederville or Superficial aquifers.

Model v. 2.0 is unsuitable for determining groundwater-level changes to the accuracy required for determining the impacts of abstraction on groundwater-dependent ecosystems (GDE's). The model can be used to show areas that could be at risk, so that further interpretation can be made and means of overcoming any impacts can be designed.

7. Provide results (above) that will support the determinations of sustainable yields based on impacts on identified groundwater dependent ecosystems (GDEs).

An objective is to determine likely impacts on GDEs dependent on the Yarragadee aquifer.

Model v. 2.0 is unsuitable for determining sustainable yields based on the impacts on GDE's. Local interpretations and models may be needed for this purpose.

8. Estimate the likely range and uncertainty of water level changes in areas affected by large-scale pumping to enable the assessment of the risk of water levels changes that may impact on GDEs.

Model is to determine likely range in water level changes with uncertainty determined by understanding of the conceptual model. Predictions in Yarragadee will be reasonably certain, with less certainty applying to other formations.

Uncertainty and sensitivity analyses can be carried out using the model for ranges of aquifer parameters, to determine the potential extent of drawdowns and which GDE's could be impacted.

9. Identify the groundwater capture area for the proposed Water Corporation scheme that will enable the determination of public drinking water source protection areas.

Concentrate on areas of Yarragadee outcrop or where there is a thin overlying Superficial aquifer. Level of protection (P1 etc.) will depend on groundwater flow rates towards the borefield.

The model can be used for this purpose.

10. Allow an evaluation of the increased risk of seawater intrusion resulting from the proposed 45 GL / yr abstraction.

The model is to determine drawdowns at the coast and provide water balances from which an assessment of the risk of seawater intrusion can be made.

The model can possibly be used for this purpose but discharge from confined aquifers to the ocean can never be closely defined, and must be based on assumptions. The analysis of risk will, therefore, be uncertain.

The model is a large regional model representing a complex, multi-layered aquifer system. It is suitable for meeting some of the stated objectives, and can be used as a tool in risk analysis of the potential impacts on GDE's and other users. Concerns raised in this review should be addressed, and the model should be updated as additional information is collected, and re-calibrated after additional stress has been applied to the aquifer.

At the present stage of its development, the model is not suitable for simulating flow within and between the Leederville and superficial aquifers and may not accurately represent groundwater flows in the Yarragadee Formation. As a result, there are uncertainties associated with predictions made using the model.

- predicting water-level drawdowns and seasonal fluctuations near other groundwater users, wetlands, rivers and streams;

- evaluating the risk of seawater intrusion associated with the planned abstraction; and

- providing results that can be used in determining sustainable yields based on the impacts on GDE's.

In addition, the model in its present form cannot be used to quantify any water flows from the Blackwood and Donnelly Rivers to aquifers that may occur at present, or as a result of the planned abstraction. The lack of this capability is inconsequential where river levels are below groundwater levels.

The model is a useful management tool for allocating groundwater resources in the region, but further refinement and calibration is required to improve its accuracy and usefulness.

8 CONCLUSIONS

SWAMS v 2.0 has enhanced the representation of the previous version of the South-West Aquifers Model, and its capabilities allow it to be used as a Risk Management Tool for derivation of qualitative water level drawdowns in areas where such drawdowns may lead to environmental risk. These could include; reduction of environmental water flows in the Blackwood River; lowering of water levels in superficial aquifers which support wetlands or where there may be potential for formation of acid sulphate soils; and reduction in pumping water levels in existing and planned private and municipal abstraction bores. This evaluation of risk can then be used to assist in borefield location and design, and to derive risk management plans where the potential for adverse impacts is indicated. SWAMS v 2.0 has in effect already been used for this purpose by relocating from the original proposed Western Borefield to the now preferred Eastern Borefield. By so doing the level of environmental risk associated with potential reduction in water flows in the Blackwood River, to the Reedia wetlands and to the formation of acid sulphate soils on the eastern Scott Coastal Plain has been reduced.

The model is suitable as a regional tool for estimating overall water budgets, and it can be used for delineating areas that could potentially be impacted by pumping. The Panel believes that SWAMS v 2.0 probably over-estimates water-level drawdowns particularly in the superficial aquifers because it does not allow for re-circulation of irrigation water or additional recharge (and reduced evapotranspiration losses) that will occur once groundwater levels are lowered.

The 45 GL/annum proposed to be abstracted by the Water Corporation is a relatively small proportion of the total groundwater flow through the Leederville and Yarragadee aquifers. Estimates of groundwater held in storage in the Yarragadee aquifer alone (at a conservative 20% porosity) indicate upwards of 1.0 million GL with considerable additional storage reserves in the adjoining more silty and clayey formations (the aquitards) which can have porosities exceeding 50% as measured in core samples from investigation drilling. This large volume of groundwater is an historical legacy deriving from accumulation of groundwater in the aquifers over tens of thousands of years through periods of fluctuating climatic, vegetation and sea level changes.

Rainfall data used in SWAMS v 2.0 are annual averages for the period 1980 to 2003, which is a period of reduced rainfall compared to available records for Perth extending back to 1876. Global warming is predicted to result in reducing rainfalls over the next decades and the impact of reduced rainfalls on recharge needs to be modelled. There is, however, no certainty that rainfalls will decline and also the use of lower than long term average rainfalls in SWAMS v 2.0 to some extent has built in a level of conservatism.

Should the borefield be commissioned The Panel considers it absolutely essential that adequate groundwater monitoring be carried out before and after commissioning, so that the model can be revised and recalibrated after the aquifers have been stressed for one to two years. In this way more reliable regional drawdown impacts can be predicted and changes to borefield design (eg. bore locations, depths of abstraction and individual bore abstraction rates) can be incorporated into the groundwater management plan at an early stage.

The Panel recommends that should a decision be made to proceed with the Eastern Borefield option then additional localised modelling be undertaken to optimise the design. The Panel is concerned that abstraction directly from the upper part of the Yarragadee aquifer (Juy1) could induce significant leakage of lower quality groundwater (higher salinity and iron content) from the overlying Leederville aquifer. Whereas abstraction solely from the deeper sections of the aquifer (Juy3) will propagate to Juy4, Juy2 and Juy1 as well as to the Leederville aquifer, but with less adverse impact on groundwater quality (and treatment costs).

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Annex A

Peer Review Panel Brief from Department of Environment

ORIGINAL BRIEF FROM DEPARTMENT OF ENVIRONMENT TO PEER REVIEW PANEL FOR REVIEW OF SWAMS V 1.2.1 ADOPTED BY WATER CORPORATION FOR REVIEW OF SWAMS V 2.0

PEER REVIEW OF THE CONCEPTUAL AND NUMERICAL GROUNDWATER FLOW MODELS OF THE SOUTHERN PERTH BASIN

1. Objectives of the modelling

The purpose of the numerical model is to replicate the conceptual hydrogeological model, and to then provide a means of assessing the likely impacts of the proposed Water Corporation scheme and other possible increases in future abstraction. Details of the modelling project are set out in the attached model brief. The objectives of Stage-1 modelling are to:

- simulate groundwater flow within and between all hydrogeological units in the southern Perth Basin that are within the active part of the groundwater flow system;
- establish a water budget for the Yarragadee aquifer;
- provide first estimates of water budgets for other aquifers;
- under a range of scenarios, including the proposed Water Corporation abstraction of 45 GL/year from one or more possible borefield locations, predict the scale of changes in groundwater potentiometric heads/water levels within the hydrogeologic units;
- evaluate likely changes in groundwater discharge to rivers (including the Blackwood River), streams and wetlands, and ocean environments;
- predict the general drawdown in water levels near other groundwater users, wetlands, and rivers and streams in the project area, and provide seasonal variations in such reductions;
- provide results (above) that will support the determinations of sustainable yields based on impacts on identified groundwater dependent ecosystems (GDEs);
- estimate the likely range and uncertainty of water level changes in areas affected by large-scale pumping to enable the assessment of the risk of water levels changes that may impact on GDEs;
- identify the groundwater capture area for the proposed Water Corporation scheme that will enable the determination of public drinking water source protection areas; and
- allow an evaluation of the increased risk of seawater intrusion resulting from the proposed 45 GL/yr abstraction.

2. Scope of works for the peer review

A peer review is best done progressively through the modelling process at key milestones (conceptualisation, end of calibration, end of prediction, and after report completion). The experience of expert reviewers will provide valuable feedback to the model's development, and will ensure a more reliable and useful product at the completion of the study. If left to the end of the study, there is a danger that a mistake could have been made early in the modelling process, which might invalidate subsequent work. The review of Stage -1 will provide valuable advice on subsequent model developments that will be used to support water management decisions in the southern Perth Basin. Peer review should assess the following aspects of the modelling (MDBC, 2002):

1. The report;
2. Data analysis;
3. Conceptualisation;
4. Model design;
5. Calibration;
6. Verification;
7. Prediction;
8. Sensitivity analysis; and
9. Uncertainty analysis.

The peer reviewer is required to develop a review methodology and present to the Project Manager for endorsement.

The scope of works of the peer review will include frequent liaison with key members of the Investigations Team, attendance at occasional meetings with SW Yarragadee project teams and other personnel involved in the project, and presentation of combined panel findings to key stakeholders as arranged by WRC. It is a requirement that a combined report on the peer review be submitted at the end the review. The combined review report is to be coordinated by the review panel member nominated by the Water and Rivers Commission.

3. Anticipated outcomes of peer review

The outcomes of this review will include:

1. a comprehensive assessment of the confidence, sensitivity and uncertainty of southern Perth Basin groundwater flow model;

2. identify aspects of the modelling system that can be improved through further data collection, calibration, and research and development;

3. enhance the confidence of using model results in decision-making processes; and

4. endorse the model for its use in meeting some or all of the objectives.

5. comment on how SWAMS v 2.0 has addressed any uncertainties from SWAMS v 1.2.1.