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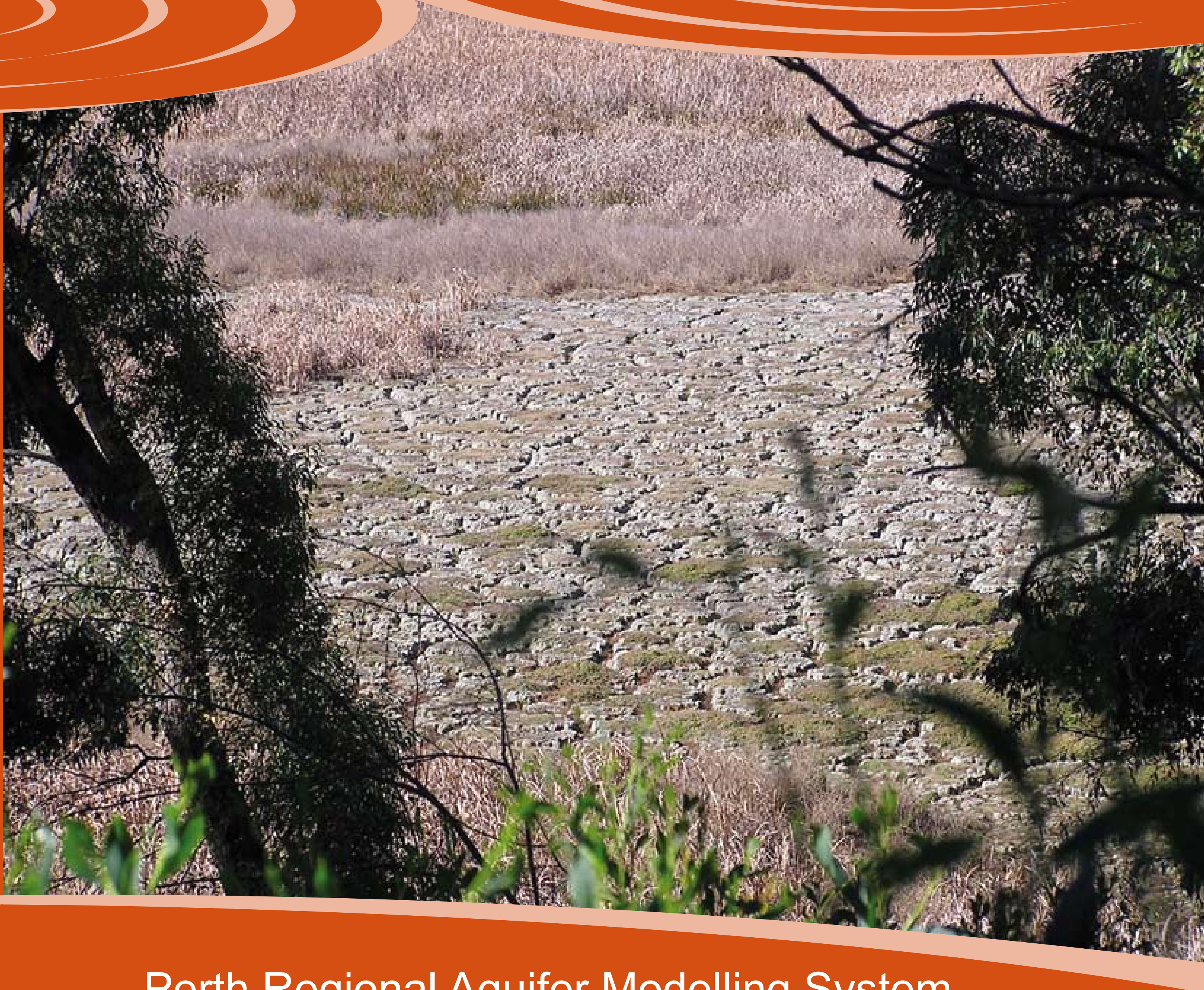

Perth Regional Aquifer Modelling System (PRAMS) model development: Review of the Coupled Perth Regional Aquifer Modelling System

Hydrogeological record series

Looking after all our water needs

Report no. HG 30
June 2009

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Department of Water
168 St Georges Terrace
Perth Western Australia 6000
Telephone +61 8 6364 7600
Facsimile +61 8 6364 7601
www.water.wa.gov.au

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For more information about this report, contact
Section Manager, Groundwater Assessment. Department of Water.

Cover photo: Dry wetlands in the northern section of Loch McNess (Wagardu Lake), Yanchep National Park, July 2006 (photo Glyn Kernick)

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Executive summary

A coupled recharge and groundwater model (PRAMS 3.0) has been developed by the Water and Rivers Commission (Department of Environment) and the Water Corporation of Western Australia. The saturated flow component of the model has been developed by CyMod Systems under contract to the Water and Rivers Commission (WRC). It is coupled to a Vertical Flux Model (VFM) that has been developed by CSIRO under contract to the Water Corporation (WC).

This report provides a peer review of the saturated flow component of PRAMS according to Australian modelling guidelines. The review is based on a checklist of 120 questions across nine model categories.

The review finds that the model has been developed competently, and is suitable for guiding regional water resource management decisions related to abstraction scenarios and changing land use scenarios. The model is not suitable for assessment at a scale less than about 500 metres, for example detailed wetland interaction. The calibration accuracy (1–4 m) also precludes local scale application. The model, however, provides an appropriate framework for extraction of local sub-models that preserve the boundary conditions of the regional model. Such models can be given finer discretisation, and would be amenable to automated re-calibration to improve the replication of the natural system.

The calibration is generally good overall. Some areas could be improved immediately by adjusting the specific yield (Superficial Aquifer) or storage coefficient (confined aquifers). It is unlikely that the calibration could be improved much more without resorting to spatial variability in aquifer properties. Where intractable bores are noted, on about 30 occasions, close examination is warranted to see if there are data or conceptual errors in those areas.

The model is of high complexity and has the benefit of more detailed stratigraphic knowledge than is likely to be found in other groundwater resource models across Australia. A common problem with all resource models is knowledge of groundwater abstraction, and the intervals from which groundwater is pumped. Although metered abstraction accounts for only half of the total abstraction, this is still known better in Western Australia than in other jurisdictions. Uncertainty in abstraction volumes and seasonal patterns is a major limitation for a resource model, as it is not possible to get highly accurate hydrographic calibrations when the major stress on the aquifer system is known poorly.

There are areas in which the model could be improved. In the short term, some adjustment to storage properties will improve the replication of cyclic amplitudes in water levels. In the longer term, automatic calibration tools can be used to reduce residual errors at key bores. This review also suggests omissions from the reports that should be covered, in particular water balance summaries.

1 Introduction

This report provides a peer review of the hydrogeological conceptualisation and groundwater flow calibration components of the Perth Regional Aquifer Modelling System (PRAMS). PRAMS is a coupled recharge and groundwater model developed by the Water and Rivers Commission (Department of Environment) and the Water Corporation of Western Australia. The saturated flow component of the PRAMS model has been developed by CyMod Systems under contract to the Water and Rivers Commission (WRC). It is coupled to a Vertical Flux Model (VFM) that has been developed by CSIRO under contract to the Water Corporation (WC). Model testing has been done by both WRC (for PRAMS) and WC (for VFM)

The model has been under development and testing since 2000, and has evolved from comprehensive prior modelling. The PRAMS model covers a large area that is approximately 60 km east-west by 210 km north-south, centred on the Perth metropolitan area. The area has a long history of groundwater use, and many of the wetlands and ecosystems are groundwater dependent. The model is intended to be an objective decision tool for the assessment of alternative resource management strategies.

The stated objectives of the PRAMS model are (CyMod Systems, 2004):

- “Estimating the impact of public and private abstraction on water levels in all aquifers;
- Provide quantitative estimates of the water resource on the Swan Coastal Plain;
- Evaluate the effects of future land use management on groundwater levels on the Swan Coastal Plain.”

Groundwater levels in the Perth region have been declining in recent years due to reduced rainfall and increasing demands for water from public schemes, industry, domestic users and horticulture. There is concern also about deteriorating water quality due to land use changes, and increasing pressure to meet ecological water requirements (EWRs) and environmental water provisions (EWPs).

2 Scope of work

The key tasks for this peer review are:

- Provide a comprehensive assessment of the confidence, sensitivity and uncertainty of PRAMS groundwater flow model;
- identify aspects of the modelling system that can be improved through further data collection, calibration, and research and development;
- enhance the confidence of using model results in decision-making processes; and
- endorse the model for its use in meeting some or all of the objectives.

3 Modelling guidelines

This review has been structured according to the checklists in the Australian Flow Modelling Guideline (Middlemis et al., 2000). This Guideline, sponsored by the Murray-Darling Basin Commission, has become a *de facto* Australian standard.

Four levels of review are advocated in the MDBC guidelines: model appraisal, peer review, model audit, and post-audit. The level of review depends on the nature of the project. The lower the complexity of the project, the less detailed a review is required. Reviews range from model appraisal for models of lower complexity, through peer review to audit for models of high complexity. An appraisal and a peer review usually involve a review of a modelling study report, while an audit also requires an in-depth review of the model data files, simulations and outputs. A post audit review is undertaken occasionally several years after the model has been completed to assess the accuracy of predictions. The guidelines also include a one-page compliance form of 10 critical questions for highlighting any corrective action that must be undertaken before the model is deemed to be acceptable.

The peer review level is appropriate for the PRAMS model, a model of high complexity. The guideline document includes a 9-page Peer Review checklist of 120 questions on the following topics:

(1) The Report;

(2) Data Analysis;

(3) Conceptualisation;

(4) Model Design;

(5) Calibration;

(6) Verification;

(7) Prediction;

(8) Sensitivity Analysis; and

(9) Uncertainty Analysis.

Not all questions in the checklists are pertinent to a site-specific model. In particular, the current PRAMS model documentation excludes the Prediction phase.

The effort put into a modelling study is very dependent on timing and budgetary constraints that are generally not known to a reviewer. Hence, reduced performance in one aspect of the modelling effort could be the result of a conscious decision by the modelling team to get the model finished on budget and/or on time, or to apply extra focus on specific issues arising during modelling.

A peer review of the vertical flux component of the study can be found in a companion report (Merrick, 2005a).

4 Evidentiary basis

The primary documentation on which the review of the groundwater flow model is based is:

1 *Davidson, W.A. and Yu, X., 2005, Perth Region Aquifer Modelling System – Hydrogeology and Groundwater Modelling. Department of Environment Hydrogeology Report No. 202, File 13488 [March 2005]. Draft Volume I, Hydrogeology and Groundwater Modelling, Perth Regional Aquifer Modelling System (PRAMS) Model Development, by Department of Environment, Government of Western Australia.*

2 *CyMod Systems, 2004, Calibration of the Coupled Perth Regional Aquifer Model – PRAMS 3.0. CyMod Systems Pty Ltd Draft Report for Water Corporation and Department of Environment Western Australia [October 2004]. Draft Volume III, Calibration of the Coupled Perth Regional Aquifer Model – PRAMS 3.0, Perth Regional Aquifer Modelling System (PRAMS) Model Development, by Department of Environment, Government of Western Australia. (In 3 volumes: Main Text; Appendices A, B, C1, C2, C3, C4, D.)*

3 *CyMod Systems, 1999, Feasibility Study for Establishing a Groundwater Modelling System for the Perth Region. CyMod Systems Pty Ltd Report for Water and Rivers Commission Western Australia and Water Corporation [December 1999]. Draft Volume IV, Associated Reports #1, Perth Regional Aquifer Modelling System (PRAMS) Model Development, by Department of Environment, Government of Western Australia.*

Additional documents were provided for the broader review of PRAMS:

4 *Silberstein, R., Barr, A., Hodgson, G., Pollock, D., Salama, R. and Hatton, T., 2004, A Vertical Flux Model for the Perth Groundwater Region. CSIRO Report for Water Corporation [October 2004]. Draft Part 1, Volume II, Perth Regional Aquifer Modelling System (PRAMS) Model Development, by Department of Environment, Government of Western Australia.*

5 *Water Corporation of Western Australia, 2004, Application of the Vertical Flux Model. Internal Report by authors CX, MC, MM, MD, BS. for Water Corporation. Draft Part 2, Volume II, Perth Regional Aquifer Modelling System (PRAMS) Model Development, by Department of Environment, Government of Western Australia.*

6 *Townley, L. R., 2000, Perth Groundwater Model: Conceptual Vertical Flux Model. Townley & Associates Pty Ltd Report for Water Corporation and Water and Rivers Commission (Western Australia) [August 2000]. Draft Volume IV, Associated Reports #2, Perth Regional Aquifer Modelling System (PRAMS) Model Development, by Department of Environment, Government of Western Australia.*

The following document underpins the modelling study:

7 *Davidson, W.A.,1995, Hydrogeology and Groundwater Resources of the Perth Region Western Australia. Geological Survey of Western Australia, Bulletin 142, 257 pp. [ISBN 0 7309 6502 3]*

The review process benefitted from several meetings held in Perth:

- 22 July 2003 – PRAMS Review Workshop (attended by ~20 local experts);
- 22 July 2003 – with Wen Yu (WRC);
- 23 July 2003 – with Chris O'Boy, Wen Yu, Binh Anson, Ryan Vogwill (WRC); Chengchao Xu (WC); Neil Milligan (CyMod);
- 24 July 2003 – with Chris O'Boy, Wen Yu, Ryan Vogwill (WRC);
- 10 September 2003 – with Wen Yu, Binh Anson, Ryan Vogwill (WRC); Michael Martin, Chengchao Xu (WC).

There is a huge body of scientific literature on the Perth Region. For practical reasons, this review is limited to information derived from the preceding documents and meeting discussions.

5 Peer review

In terms of the modelling guidelines, the PRAMS model is best categorised as an Aquifer Simulator of high complexity. An Aquifer Simulator is a high complexity representation of the groundwater system, suitable for predicting the response of a system to arbitrary changes in hydrogeological conditions.

The peer review checklists are presented in Tables 1 to 9. As prediction is yet to be done, this phase is omitted from review.

Table 1 Model review – The report: Vol. I (Hydrogeology and groundwater modelling)

Q.	Question	Not applicable or unknown	Score 0	Score 1	Score 3	Score 5	Comment
1.1	Is a report provided?		No			Yes	65 pages + 140 figures + 8 tables
1.2	Are relevant prior or companion reports provided or accessible?		No		Yes		
1.3	Is it clear which person(s) did the modelling?		No		Yes		
1.4	Is the report well structured?			Deficient	Adequate	Very good	
1.5	Is the report presentation of acceptable quality?			Deficient	Adequate	Very good	Some spelling errors
1.6	Is there a clear statement of project objectives?		Missing	Deficient	Adequate	Very good	
1.7	Is the level of model complexity clear or acknowledged?		Missing	No	Yes		High complexity, not stated explicitly
1.8	Are model parameter distributions disclosed?		Missing	Deficient	Adequate	Very good	Literature review for initial K; substantial stratigraphy
1.9	Are model parameter statistics reported (median, range, standard deviation)?		Missing	Deficient	Adequate	Very good	Pre-modelling ranges are stated.
1.10	Is it clear how stress datasets have been compiled?		Missing	Deficient	Adequate	Very good	Description of VFM (rain & ET), abstraction (growth assumption), drains. Not clear if RIV package is used.
1.11	Would it be possible to re-create the structure of the model from what is reported?			No	Maybe	Yes	Full detail on layer elevations
1.12	Is a water or mass balance reported?		Missing	Deficient	Adequate	Very good	No summary of pre-modelling water balance estimates, but recharge estimates for some aquifers, abstraction volumes, and creek baseflow.
1.13	Are recommendations reasonable and supported by evidence?		Missing	Deficient	Adequate	Very good	For conceptualisation and model development
1.14	Has the modelling study satisfied project objectives?		Missing	Deficient	Adequate	Very good	This report is limited to conceptualisation and model structure
1.15	Are the model results of any practical use?	N/A		No	Maybe	Yes	This report is limited to conceptualisation and model structure
1.16	Has the modelling study been cost-effective?	Unknown		No	Maybe	Yes	Unknown to reviewer.
1.	**Total score**						

Table 2 Model review – The report: Vol. III (Calibration)

Q.	Question	Not applicable or unknown	Score 0	Score 1	Score 3	Score 5	Comment
1.1	Is a report provided?		No			Yes	53 pages + 52 figures + 4 Appendices
1.2	Are relevant prior or companion reports provided or accessible?		No		Yes		
1.3	Is it clear which person(s) did the modelling?		No		Yes		
1.4	Is the report well structured?			Deficient	Adequate	Very good	
1.5	Is the report presentation of acceptable quality?			Deficient	Adequate	Very good	Some faulty figures, tables, pagination, grammar
1.6	Is there a clear statement of project objectives?		Missing	Deficient	Adequate	Very good	
1.7	Is the level of model complexity clear or acknowledged?		Missing	No	Yes		High complexity
1.8	Are model parameter distributions disclosed?		Missing	Deficient	Adequate	Very good	Calibrated zone values for Kh, Kz, S.
1.9	Are model parameter statistics reported (median, range, standard deviation)?		Missing	Deficient	Adequate	Very good	Expected ranges in Table 3-2. Graphical ranges in figures. No statistics or correlation with expected values (difficult to do).
1.10	Is it clear how stress datasets have been compiled?		Missing	Deficient	Adequate	Very good	Not clear how much of the natural drainage network is modelled; is RIV ever used?
1.11	Would it be possible to re-create the structure of the model from what is reported?			No	Maybe	Yes	Full detail on property distributions.
1.12	Is a water or mass balance reported?		Missing	Deficient	Adequate	Very good	Incomplete. No summary diagram or table for all recharge and discharge. No value for drain discharge. Table 5.1 (% rain) and Appendix D have missing headers.
1.13	Are recommendations reasonable and supported by evidence?		Missing	Deficient	Adequate	Very good	For model update
1.14	Has the modelling study satisfied project objectives?		Missing	Deficient	Adequate	Very good	Two objectives relate to prediction – yet to be done. Third objective relates to water resource quantification – while the model has done this, it is not reported in readily useful terms.

Table 2 Model review – The report: Vol. III (Calibration) (continued)

Q.	Question	Not applicable or unknown	Score 0	Score 1	Score 3	Score 5	Comment
1.15	Are the model results of any practical use?			No	Maybe	Yes	The model is a worthwhile tool. Most monitoring bores are well calibrated. Simulation accuracy is commonly 1–3 m, hence utility of the model is restricted to regional assessment (not detailed wetland interaction).
1.16	Has the modelling study been cost-effective?	Unknown		No	Maybe	Yes	Unknown to reviewer.
1.	**Total score**						

Table 3 Model review – Data analysis: PRAMS groundwater model

Q.	Question	Not applicable or unknown	Score 0	Score 1	Score 3	Score 5	Comment
2.1	Have prior investigations been examined and acknowledged?		Missing	Deficient	Adequate	Very good	Evolution from earlier models.
2.2	Is current knowledge sufficient for a mathematical model?			No	Maybe	Yes	
2.3	Is there a cost-effective alternative to modelling which would satisfy the project objectives?			Yes	Maybe	No	A model is essential for quantifying interactions.
2.4	Has a literature review been completed?		Missing	Deficient	Adequate	Very good	Local studies.
2.5	Has hydrogeology data been collected and analysed?		Missing	Deficient	Adequate	Very good	Extensive.
2.6	Has rainfall data been collected and analysed?		Missing	Deficient	Adequate	Very good	Collected at 5 stations. Monthly pattern, range across model area, no statistics.
2.7	Has streamflow data been collected and analysed?		Missing	Deficient	Adequate	Very good	Collected but not used. Useful baseflow/streamflow ratios. Could use baseflows as calibration targets.
2.8	Has flood event data been collected and analysed?	N/A	Missing	Deficient	Adequate	Very good	Unlikely process.
2.9	Has irrigation data been collected and analysed?		Missing	Deficient	Adequate	Very good	Estimated by reducing net abstraction from Superficial aquifer
2.10	Has groundwater usage data been collected and analysed?		Missing	Deficient	Adequate	Very good	WC records plus inferred volumes from allocations and growth factor. No metering of private licensed bores. Important limitation. Good information on use profile.
2.11	Has evapotranspiration data been collected and analysed?		Missing	Deficient	Adequate	Very good	Collected. Incorporated in VFM.
2.12	Has drainage data been collected and analysed?		Missing	Deficient	Adequate	Very good	Manmade drains. Not clear where they are, or how significant.
2.13	Has other data been collected and analysed?		Missing	Deficient	Adequate	Very good	Other data: land use, geomorphology, wetlands.
2.14	Have the above stress datasets been analysed for their groundwater response?		Missing	Deficient	Adequate	Very good	No presentation of representative hydrographs having clear signatures for rain response, stream interaction, drain control, usage impact. Vol. I has stable and declining examples.

Table 3 Model review – Data analysis: PRAMS groundwater model (continued)

Q.	Question	Not applicable or unknown	Score 0	Score 1	Score 3	Score 5	Comment
2.15	Is any relevant dataset ignored?		Yes	Maybe		No	Vertical head differences at nested bores could be examined. Coffee rock could have local effects in Superficial Aquifer.
2.16	Are residual mass (cumulative deviation) plots prepared for rainfall / streamflow?		Missing	Deficient	Adequate	Very good	10 year moving average instead (rainfall). Linear trend for streamflow.
2.17	Is groundwater hydrographic data available?			No	Maybe	Yes	Huge data set.
2.18	Are representative hydrographs selected logically?		Missing	Deficient	Adequate	Very good	All are used. Could have saved time by using a subset.
2.19	Are field hydrographs compared and analysed?		Missing	Deficient	Adequate	Very good	Two examples in Vol. I for declining and stable water levels, but no correlation with climate or abstraction.
2.20	Is water table / piezometric surface data available?			No	Maybe	Yes	
2.21	Are representative contour maps selected logically?		Missing	Deficient	Adequate	Very good	No simulated water level maps are presented. No target water level surfaces for calibration.
2.22	Is interpolation reliability clear to the reader (posting of sample points, algorithm)?		Missing	Deficient	Adequate	Very good	
2.23	Are data units consistent?			No	Yes		
2.24	Have standard geometrical datums been used?			No	Maybe	Yes	Locality Map in Vol. III should show coordinates. MGA.
2.25	If groundwater flow is likely to be affected by density, has allowance been made for the effect in any way?		Missing	Deficient	Adequate	Very good	Has been considered. Evidence of offshore salinity interface. Typical salinities do not warrant density modelling. Could be local impacts in tidal zones.
2.	**Total score**						

Table 4 Model review – Conceptualisation: PRAMS groundwater model

Q.	Question	Not applicable or unknown	Score 0	Score 1	Score 3	Score 5	Comment
3.1	Is the conceptual model consistent with prior knowledge?		Unknown	No	Maybe	Yes	
3.2	Is the conceptual model consistent with project budget?		Unknown	No	Maybe	Yes	
3.3	Is the conceptual model consistent with project objectives and the required model complexity?		Unknown	No	Maybe	Yes	High complexity aquifer simulator model.
3.4	Is the conceptual model consistent with project deadline?		Unknown	No	Maybe	Yes	Lengthy timeframe for model development. Includes R&D component (VFM).
3.5	Is there a clear description of the conceptual model?		Missing	Deficient	Adequate	Very good	Detailed description of each aquifer and aquitard, and interactions. Better knowledge of stratigraphy than other models in Australia.
3.6	Is there a graphical representation of the modeller's conceptualisation?		Missing	Deficient	Adequate	Very good	Good graphics – Figs. 100,101.
3.7	Is the conceptual model unnecessarily simple?			Yes	No		
3.8	Is the conceptual model unnecessarily complex?			Yes	No		Very complex, but justified. Could work just as well with fewer layers. Little advantage in undoing work that has been done.
3.9	If any possibly key process is missing, is the justification adequate?		Missing	Deficient	Adequate	Very good	Not clear if gaining/losing streams are simulated. Possibility of enhanced recharge due to runoff from Darling Scarp (can't handle with VFM).
3.10	Are limitations and uncertainties described?			No	Maybe	Yes	Extensively
3.11	Has the conceptual model been reviewed independently?		Unknown	No	Maybe	Yes	Based on extensive prior investigations over > 30 years. Some areas undrilled.
3.	**Total score**						

Table 5 Model review – Model design: PRAMS groundwater model

Q.	Question	Not applicable or unknown	Score 0	Score 1	Score 3	Score 5	Comment
4.1	Is the choice of mathematical model appropriate (analytical / numerical)?			No	Maybe	Yes	Has to be numerical.
4.2	Is the spatial extent of the model appropriate?			No	Maybe	Yes	Extends offshore.
4.3	Is the spatial discretisation scale appropriate?		Missing	No	Maybe	Yes	500 m square cells. No statement of #rows (454), #columns (214). Suitable for regional analysis. Not suitable for detailed wetlands interaction. Finer discretisation would generate too many model cells.
4.4	Is the number of model layers justified?		Missing	No	Maybe	Yes	12 layers. Might be overkill.
4.5	Is steady state simulated?		Missing	Deficient	Adequate	Very good	1980 quasi steady-state. Stated but not shown.
4.6	Is transient behaviour simulated?		Missing	Deficient	Adequate	Very good	Many hydrographs over a long period. 20 year simulation 1980–2000.
4.7	Is the stress period reasonable?		Missing	No	Maybe	Yes	Monthly.
4.8	Is the number of time steps per stress period justified?		Missing	Deficient	Adequate	Very good	4–8
4.9	Are the applied boundary conditions plausible and unrestrictive?		Missing	Deficient	Adequate	Very good	Natural boundaries wherever possible. Western boundary is uncertain, based on inferred fault control. Southern boundary a little close to expanding abstraction from Yarragadee. No drawdown maps (with vs without pumping) to guide influence of boundaries. Ocean constant head 0.5 m AHD. Northern boundary – chosen to ignore 10 ML/day inflow.
4.10	Are boundary condition locations consistent with the model grid configuration?		Missing	No	Maybe	Yes	
4.11	Are the initial conditions defensible?		Missing	Deficient	Adequate	Very good	Steady state heads at 1980. Then transient to 1985.
4.12	Is it clear what software has been selected?		Missing	No	Maybe	Yes	Vol. I suggests GMS. Vol. III has no statement. Software used is believed to be PMWIN – what version?
4.13	Is the software appropriate for the objectives of the study?			No	Maybe	Yes	

Table 5 Model review – Model design: PRAMS groundwater model (continued)

Q.	Question	Not applicable or unknown	Score 0	Score 1	Score 3	Score 5	Comment
4.14	Is the software reputable?			No	Maybe	Yes	
4.15	Is the software in common use and accessible to reviewers?			No	Maybe	Yes	
4.16	How detailed is the rainfall recharge algorithm?		Missing	Deficient	Adequate	Very good	VFM.
4.	**Total score**						

Table 6 Model review – Calibration: PRAMS groundwater model

Q.	Question	Not applicable or unknown	Score 0	Score 1	Score 3	Score 5	Comment
5.1	Is sufficient data available for spatial calibration?			No	Maybe	Yes	Limited data to the north and northeast.
5.2	Is sufficient data available for temporal calibration?			No	Maybe	Yes	Plenty (862 bores). From 1968.
5.3	Does the model claim to be adequately calibrated for the purpose of the study?		Missing	No	Maybe	Yes	Some intractable calibration is acknowledged. Spot bores, some trends.
5.4	Are calibration difficulties acknowledged?		Missing	Deficient	Adequate	Very good	Open discussion on bias in some layers. Guildford Clay presents difficulties. Some areas require reconceptualisation.
5.5	Is it clear whether calibration is automated or trial-and-error?		Missing	No		Yes	Manual.
5.6	Is there sufficient evidence provided for model calibration?		Missing	Deficient	Adequate	Very good	All hydrograph matches are given, with calibration error graph and statistics for each bore. Scattergrams for main aquifers. No presentation of spatial water level matches, other than spatial residual error at one date (October 1992).
5.7	Is the model sufficiently calibrated against spatial observations?		Missing	Deficient	Adequate	Very good	Typical accuracy 1–4 m across a range in heads of 0 to > 100 m AHD (range not stated).
5.8	Is the model sufficiently calibrated against temporal observations?		Missing	Deficient	Adequate	Very good	Cyclic pattern well captured. Amplitudes could be improved in many places. Some systematic offsets. Good overall.
5.9	Are parts of the model well calibrated?		Unknown	No	Maybe	Yes	Many bores within 1 m.
5.10	Are parts of the model poorly calibrated?		Unknown	Yes	Maybe	No	About 30 Bores > 5 m error. Southern Yarragadee shows flat response in area of declining water levels.
5.11	Is the model calibrated to data from different hydrological regimes?		Unknown	No	Maybe	Yes	Covers long period with climate variability, growth in abstraction, and changing land use.
5.12	Are calibrated parameter distributions and ranges plausible?		Missing	No	Maybe	Yes	

Table 6 Model review – Calibration: PRAMS groundwater model (continued)

Q.	Question	Not applicable or unknown	Score 0	Score 1	Score 3	Score 5	Comment
5.13	Is a calibration statistic reported?		Missing	No		Yes	Reported as Average Absolute and Average RMS errors for each major aquifer. Could also report as RMS – expect < 5% with this model – OK.
5.14	Does the calibration statistic satisfy agreed performance criteria?	N/A	Missing	Deficient	Adequate	Very good	
5.15	Are there good reasons for not meeting agreed performance criteria?	N/A	Missing	Deficient	Adequate	Very good	
5.	**Total score**						

Table 7 Model review – Verification: PRAMS groundwater model

Q.	Question	Not applicable or unknown	Score 0	Score 1	Score 3	Score 5	Comment
6.1	Has some data been reserved for a verification exercise?		Missing	No	Maybe	Yes	
6.2	Is the reserved data set an extension of the time period?		Missing	No	Maybe	Yes	
6.3	Is the reserved dataset a suite of hydrographs not on the representative list?		Missing	No	Maybe	Yes	All hydrographs have been used for calibration.
6.4	Is the volume of reserved data sufficient to establish verification?		Unknown	No	Maybe	Yes	4 years. January 2000–January 2004.
6.5	Does the model claim to be verified?		Missing	No	Maybe	Yes	Some reservations. Marginally worse performance than calibration period, but still quite good. Improvement in Mirrabooka Aquifer.
6.6	Is there sufficient evidence provided for model verification?		Missing	Deficient	Adequate	Very good	> 800 hydrographs.
6.7	Are parts of the model well verified?		Unknown	No	Maybe	Yes	No worse than calibration.
6.8	Are parts of the model poorly verified?		Unknown	Yes	Maybe	No	Where assumed abstraction is overestimated, simulated levels decline too fast.
6.9	Is the reserved dataset from a different hydrological regime?		Unknown	No	Maybe	Yes	Lower rain, more abstraction, changing land use.
6.10	Does the reserved dataset include stresses consistent with the prediction scenarios?	N/A	Unknown	No	Maybe	Yes	No prediction yet.
6.11	Are there good reasons for an unsatisfactory verification?		Missing	Deficient	Adequate	Very good	Uncertainty in abstraction – lack of metering.
6.	**Total score**						

Table 8 Model review – Sensitivity analysis: PRAMS groundwater model

Q.	Question	Not applicable or unknown	Score 0	Score 1	Score 3	Score 5	Comment
8.1	Is there discussion of qualitative sensitivities found during calibration?		Missing	Deficient	Adequate	Very good	
8.2	Has a post-calibration sensitivity analysis been performed?		Missing	Deficient	Adequate	Very good	Done for 3 parameters: Kh, Kz, S. Recharge parameters done separately with VFM component. Could have done boundary conditions, spatial zonation – but huge task.
8.3	Is the sensitivity analysis sufficiently intensive for key parameters?		Missing	Deficient	Adequate	Very good	3 runs of Modflow 2000 to give automatic sensitivity coefficients.
8.4	Is there a graphical presentation of sensitivity behaviour?		Missing	Deficient	Adequate	Very good	
8.5	Are sensitivities classified as Type I to Type IV?		Missing	No		Yes	*See Guidelines Section 5.3*
8.6	Has a Type IV sensitivity been recognised?		Missing	Yes	Maybe	No	*See Guidelines Section 5.3*
8.7	Is there a list of ranked sensitivity coefficients?		Missing	Deficient	Adequate	Very good	Quantitative coefficients are presented but not explained. Colour coding of importance has been lost with B&W print. Table 6-2 incomplete. Also, list of most sensitive bores.
8.8	Are sensitivity results used to qualify the reliability of model calibration?		Missing	Deficient	Adequate	Very good	
8.9	Are sensitivity results used to qualify the accuracy of model prediction?	N/A	Missing	Deficient	Adequate	Very good	No prediction yet.
8.	**Total score**						

Table 9 Model review – Uncertainty analysis: PRAMS groundwater model

Q.	Question	Not applicable or unknown	Score 0	Score 1	Score 3	Score 5	Comment
9.1	Is the uncertainty in aquifer properties acknowledged or described/quantified?		Missing	Deficient	Adequate	Very good	Based on reported ranges. No spatial variation within zones. Geology uncertainties in Vol. I – coffee rock, Guildford Clay, Kings Park Fm., faults.
9.2	Are uncertainties in stress datasets acknowledged or described/quantified?		Missing	Deficient	Adequate	Very good	Especially groundwater use.
9.3	Are uncertainties in observation data acknowledged or described/quantified?		Missing	Deficient	Adequate	Very good	Especially to the north and northeast. Some database quality control issues.
9.4	Are uncertainties in predicted outcomes acknowledged or described/quantified?	N/A	Missing	Deficient	Adequate	Very good	No prediction yet.
9.5	If required by the project brief, is uncertainty quantified in any way?	N/A	Missing	No	Maybe	Yes	Statement of model limitations in Vol. I and Vol. III.
9.6	If uncertainty has been quantified, has an acceptable method been used?	N/A	Missing	Deficient	Adequate	Very good	Method:
9.7	If uncertainty has been quantified, how extensive is the analysis?	N/A	Missing	Deficient	Adequate	Very good	Not quantified with flow model. Extensive analysis of VFM by FOSM.
9.	**Total score**						

6 Discussion

6.1 The report

Tables 1 and 2 assess the quality of the two reports on the flow model, Documents #1 and #2 (defined in Section 4).

Document #1 on the hydrogeology and groundwater model setup is a high quality document. Some spelling errors need correction. To an external reader with no prior knowledge of the study area, the report comes close to being a standalone document, although additional useful data can be found in supporting documents. The report includes an expansive section on stratigraphy, and includes structure contours and isopach maps for each lithological unit in each layer. To enhance the discussion on conceptualisation, there should be a selection of representative hydrographs showing clear responses to rainfall, streamflow, drainage, and abstraction. In addition, hydrographs close to the same location at different depths could illustrate vertical gradients. Figure 80, showing zones of inferred upward and downward leakage, is a useful indicator of system behaviour. Pre-modelling water balance components should be summarised in a table.

Document #2 on calibration is of lower quality, and requires correction of many figures, tables, pagination, and grammar. While there is complete presentation of hydrographic performance for more than 800 bores, there is no presentation of spatial performance by comparing observed and simulated water level contours for the main aquifers. Portrayal of representative residual errors, for a particular date, is a useful indicator of system performance. However, the use of the average residual error reported with each hydrograph might be more diagnostic. Post-calibration water balance components should be summarised in a table or graphic. There is common reference to particular bore names with no supporting location plan, or description of general location, rendering much of the discussion unintelligible to an external reader with no prior knowledge of the study area.

Detailed editorial corrections are offered in the Appendices.

6.2 Data analysis

Fundamental data sets (stratigraphy, geology, land use, climate, streamflow, abstraction) are included in the reports but there is no reported analysis of hydrographic responses to stresses as a basis for the conceptual model. This has probably been done, and the necessity for doing so could have been downgraded in importance given the evolutionary nature of this model, being an update on earlier models with clear conceptualisation of dominant processes. Comparison of rainfall residual mass (cumulative deviation from the mean, CDFM) with a representative hydrograph would have shown clearly the frequent dependence of long-wavelength groundwater behaviour on rainfall infiltration. As cyclic groundwater response is a feature of most hydrographs, there should be a clear statement of what is causing this, or a correlation with abstraction or seasonal irrigation.

Streamflow data are presented but not used. Such data are very useful as calibration targets, and should be used in this way in future modelling.

Despite good metered records for public scheme use of groundwater, there is large uncertainty in abstraction by licensed and unlicensed private bores, and in the growth algorithm that has had to be invoked. This clearly is a major impediment in achieving calibration of a higher accuracy. Metered and unmetered volumes are roughly of the same order. This is a common limitation in resource models across Australia, but knowledge here is better than usual.

6.3 Conceptualisation

A conceptual model diagram is a simplified 2D or 3D summary picture (without stratigraphic detail) that conveys the essential features of the hydrological system, denoting all recharge/discharge processes that are likely to be significant. The diagram can serve a dual purpose for displaying the magnitudes of the water budget components derived from data sources or from simulation. Document #1 reports a thorough schematic section in Figure 100, and a stratigraphic block diagram in Figure 101.

The model conceptualisation is reported and illustrated in great detail. Vertical discretisation into 12 layers is probably overkill, but there is no point in undoing a lot of good work in mapping the structure. The knowledge of stratigraphy is better than other comparable resource models across Australia.

The hydrostratigraphic conceptualisation is well supported by evidence, but it is recognised that there is still some uncertainty with the Kings Park Formation, the foothill areas along the Gingin and Darling Scarps, and the hydraulic influence of numerous faults, particularly offshore. This uncertainty imposes a limitation on the model.

It is stated that most water bodies are permanent drains, and some streams have both losing and gaining functions in different reaches. It is not clear if such streams have been simulated appropriately in the model (using the river package, RIV). A similar feature should be used for throughflow lakes.

6.4 Model design

The model uses the USGS standard, MODFLOW, but surprisingly there is no statement on what graphic user interface is used. This is believed to be PM Pro, but Document #1 gives the impression that GMS is being used.

Discretisation in space and time is appropriate. Aquifer properties have been set at uniform values within designated zones in each layer, and stresses are dynamic. The grid consists of cells that are 500 metres square, but there is no statement of the numbers of rows and columns. It is understood that the corresponding numbers are 454 and 214. In that case, making the cells smaller would give an unmanageable number of cells. A size of 500 m is suitable for regional analysis, particularly for the stated objectives of the model, namely for assessing the regional impact of abstraction and land use scenarios. The model is not suitable for assessment at a finer scale, for example detailed wetland interaction. The calibration accuracy (1–4 m) also precludes local scale application. The model, however, provides an appropriate framework for extraction of local sub-models by telescopic mesh refinement (TMR). Such models can be given finer discretisation, and would be amenable to automated re-calibration to reduce the calibration error.

Boundary conditions are set appropriately, despite some uncertainty offshore. The southern boundary is perhaps a little close to expanding abstraction from the Yarragadee aquifer. The model could have been used to produce a drawdown map due to current pumping, by running a base case with no pumping. This would give some insight into the influence of the boundaries. At the northern boundary, there has been a deliberate decision to ignore 10 ML/day lateral flow across the boundary. This is reasonable for the time being, until better knowledge is gained on groundwater levels in that area.

The constant head boundary along the shoreline has been set at 0.5 m AHD. This is a reasonable action, due to the inertia of groundwater discharge within a tidal cycle and correction for water density.

There is no diagram of the model grid. This would help the reader gain an impression of the roughness/fineness of discretisation.

6.5 Calibration

On the whole, the model is quite well calibrated against individual hydrographs. The approach to calibration is manual, or trial-and-error, and it is difficult to achieve simultaneous good calibrations everywhere using this approach. Some bores are matched almost perfectly, indicating correct conceptualisation and correct parameterisation. For others the trends are matched very well, but there is a systematic offset. This is not a concern in a regional model, as long as the purpose remains regional assessment of abstraction and land use impacts. With effort, the offset can be collapsed by local changes in horizontal hydraulic conductivity. In relatively few bores (less than 5%), there are intractable errors in excess of 5 metres.

In general, hydrographic trends are well captured. The exception is the southern Yarragadee aquifer, where the model reports stable water levels while bores show a clear decline with time. The problem might be due to a constraining offshore boundary condition. The reason should be investigated.

The level of accuracy is in the order of 2 m, on average, in the Superficial Aquifer, and around 4 m in the confined aquifers.

Calibration in the Superficial Aquifer is very good in general, with clear offsets at many bores. The frequency of oscillation is captured well in the hydrographs, although the amplitudes are often wrong. Much improved calibrations could be achieved by allowing spatial variability in specific yield, which is allowed to vary in zones from 0.05 to 0.25. Two areas clearly require higher specific yield:

- Along most of the Swan River;
- Rockingham – Kwinana area.

It is recommended that the amplitudes of the observed and simulated hydrographs be measured to give a correction factor for specific yield. It is important to get the Superficial water levels as accurate as possible, as this impacts on the validity of coupling with the VFM, which requires an accurate depth to shallow water tables. However, VFM recharge is insensitive to fluctuations in deeper water tables (more than 4 metres below ground; Merrick, 2005a). For bores with intractable errors, close examination is required to see whether there is a conceptualisation or data error. For example, bore JP7 on the coast has a simulated value of about 6 m AHD; there must be something wrong here.

For the Mirrabooka Aquifer, calibration is good but there is a tendency to underestimation of heads. Several bores have more than 5 m residual error. Three southern bores show a rising water level when it should be falling. Based on relative amplitudes, the central bores all require higher storage coefficient, while the northern bores require lower storage coefficient.

For the Leederville Aquifer most amplitudes are good, but there are occasions where higher or lower storage coefficient would help. Lower S is required near the Kings Park channel (near AM36) and Jandakot (near AM46). There are two instances at Jandakot (AM48, AM51) where the response is flat but the measurements show a decline in water level. Lower S is also required near Yanchep (AM1 to AM12)

The declining water level in the southern part of the Yarragadee Aquifer (south of Jandakot) is not captured by the model, and simulated levels are generally more than 5 metres too high. There is one extensive zone that clearly requires higher storage coefficient, stretching from AM52 near Jandakot to AM31 near Guildford. There is a number of very good calibrations in the vicinity of Perth.

The baseflows to the streams have not been used during calibration. As the water balance from the calibrated model reports gross discharge to drain features, this should be checked against measurements for correct magnitude. The next phase of calibration should be cognisant of this extra information.

Another check on model performance is provided by Figure 80 in Document #1. This shows inferred areas of downward discharge from, and upward recharge to, the

Superficial Aquifer. The polarity of the simulated head differences between the upper model layers should replicate this pattern.

Better simultaneous hydrographic matches at all sites probably cannot be achieved without incorporating more spatial variability into the hydraulic conductivity distribution. The model has uniform properties in a mosaic of zones in each layer. Realistically, this cannot be taken any further by manual calibration. Automated calibration would be possible but difficult given the sheer volume of data. To make use of the full data set, Parallel PEST (across a network of computers) with pilot points for hydraulic conductivity would have to be used. A compromise would be to select calibration targets from a subset of bores for only two seasons. Then, PEST could be run on a single computer, but it might take a day or two to run. Alternatively, PEST could be deferred for use with sub-models only, as they will have fewer target data. Baseflow can be included as a PEST calibration target.

Calibration against water level contour maps at different times has not been reported. It is likely that the performance would be quite good.

6.6 Verification

Temporal verification has been performed by extending the model simulation by four years beyond the calibration timeframe. The performance of the model during the verification period is quite good, and only marginally worse than the calibration period. For the Mirrabooka Aquifer, the performance has improved.

The verification period differs from the calibration period in having lower rain (although the amount is not stated), changing land use, and increasing groundwater abstraction. At some bores the model anticipates water level declines at a rate faster than observed. This is due to an overestimation in groundwater abstraction at bores that are not metered.

6.7 Sensitivity analysis

On such a large model, sensitivity analysis is difficult to do thoroughly. Here, three runs have been made with perturbed hydraulic conductivities (horizontal and vertical) and storativity. The innate features of MODFLOW 2000 have been used to compute normalised sensitivity coefficients. The reader is given no help in understanding what these coefficients mean, whether high or low numbers are favourable, and what the matrix structure means in Table 6-2. A colour coding scheme in Table 6-2 is used to highlight the most important parameters, but the colours have been lost in black-and-white reproduction. There are many cells in Table 6-2 with missing values, including all of the cells marked most important. Hence, the reporting on sensitivity analysis is inadequate.

Other features that could be tested for sensitivity are the western boundary condition (to see if this affects the rate of decline in southern Yarragadee water levels), spatial zonation (to see if this corrects systematic offsets), and abstraction growth factor.

Given coupling with the VFM, it is too difficult to do a sensitivity analysis on rainfall/ irrigation recharge estimates. A sensible approach has been followed here by decoupling from the VFM and running with a predetermined recharge schedule.

6.8 Uncertainty analysis

No formal uncertainty analysis has been undertaken, but this is not unusual. This activity should not be expected unless it is called for in the project brief and is funded accordingly.

There is frequent acknowledgement in Documents #1 and #2 of the limitations in the model. Geology uncertainties exist with coffee rock, Guildford Clay, Kings Park Formation, and faults. Data uncertainties exist mostly to the north and northeast, with some database quality control issues. Stress uncertainties are dominated by unmetered groundwater abstraction, assumed growth factor, and the validity of recharge calculated by the Vertical Flux Model.

7 Recommendations

The PRAMS 3.0 groundwater model has been developed competently, and is suitable for guiding regional water resource management decisions related to abstraction scenarios and changing land use scenarios. The model is not suitable for assessment at a scale less than about 500 metres, for example detailed wetland interaction. The calibration accuracy (1-4 m) also precludes local scale application. The model, however, provides an appropriate framework for extraction of local sub-models by telescopic mesh refinement (TMR). Such models can be given finer discretisation, and would be amenable to automated re-calibration to reduce the calibration error.

The calibration is generally good overall. Some areas could be improved immediately by adjusting the specific yield (Superficial Aquifer) or storage coefficient (confined aquifers). It is unlikely that the calibration could be improved much more without resorting to spatial variability in aquifer properties. Some intractable bores are noted.

The following recommendations are made:

- That specific yield and storage coefficient be adjusted in two zones in the Superficial Aquifer, two zones in the Mirrabooka Aquifer, two zones in the Leederville Aquifer, and one zone in the Yarragadee Aquifer; the correction should be estimated by measuring the relative amplitudes of observed and simulated responses in these areas;
- That the explanation of sensitivity analysis outputs be improved;
- That pre-model and post-model water balance summaries be incorporated in the two reports;
- That intractable bores (about 30) be examined closely for conceptual or data errors;
- That water level contour maps be included in the calibration report;
- That the model be run once with less constraint in the western boundary condition to see if this overcomes a possible conceptual error in the southern Yarragadee, where the model does not replicate falling water levels;
- That editorial corrections be made to the two reports, as detailed in the Appendices to this review.

Although not essential at this time, the following suggestions are made for further development of the model:

- That spatial variability be explored as a way of improving calibration of bore hydrographs with systematic offsets; this is best done by automated calibration (using PEST) on a small subset of target bores for two years of data, using the pre-determined VFM recharge schedule;

- That stream baseflows be included as calibration targets;
- That sub-models be extracted from the regional model for local scale assessment; the sub-models would benefit from automated re-calibration with flexibility in the spatial variability of formation properties.

8 References

Middlemis, H., Merrick, N. P, and Ross, J. B., 2000, *Groundwater Modelling Guidelines*. Aquaterra Report for Murray Darling Basin Commission, October 2000, 125 p.

Merrick, N.P., 2005a, *Review of the Vertical Flux Model Component of the Perth Regional Aquifer Modelling System*. AccessUTS Report for Water and Rivers Commission, Project C03/044/006. Draft: November 2005, 18 p.

Appendix 1 Amendments to Document #1

1.1 Location

Murray River is not marked on Figure 1.

1.4 Previous work

Misspelling of “hydrogeological” in 1.4.1 header.
Page 4, Line 1: studies → studied.
Page 5: have poses → pose.

1.5 Modelling system

Page 6, third para: Talks of GMS being recommended. Need to explain why a different system was implemented, and what it is.
Page 6, fourth para: dimeional → dimensional.

2.3 Geomorphology

Darling Plateau: refer to Figure 5.
Page 11, second last para: clarify the definition of the width of the capture zone – is it one side or both sides of a lake?

4.1 Superficial aquifer

Page 25, second last para: Fig. 78 → Fig. 79.
Page 25, last para: Fig. 79 → Fig. 78.
Page 26, third last para: Fig. 79 → Fig. 78.
Page 26, last line: gradients → gradient.
Page 27, third para: Fig. 81 → Fig. 80.
Page 27, fourth para: where are Stakehill Mound & Safety Bay Mound? Absent → absence.
Page 27, third last para: give references for statements on infiltration as a percentage of rainfall.
Page 28, first para: Fig. 81 → Fig. 80.

4.4 Mirrabooka aquifer

Page 30: Comment on water quality.
Page 31, last para: the stated “volume of groundwater in storage” is not correct; porosity determines storage, storage coefficient determines the extractable volume.

4.5 Leederville aquifer

Page 32: Comment on water quality.
Page 32, fourth para: is given → are given.
Page 32, fifth para: Refer to Fig. 91.
Page 33, first para: The referenced 5 m contour is no shown in Fig. 90.
Page 36, second last para: Comment on broad 10 m sink south of Perth (Fig. 99).
Page 37: What is the maximum salinity in the Yarragadee? Is the salinity depth profile known?

5.1 Introduction (Groundwater modelling)

Page 38, fifth para: Refer to Fig. 8 for Pinjar Anticline.

5.2 Model layout

Page 39, first para: Setting the top of Layer 1 at the watertable (which one?) is strange practice; it precludes reporting of predicted depth-to-water maps. As VFM requires depth to water, not water elevation, where is the surface topography data held – in VFM? The model will at times calculate water levels above the top of Layer 1. While this is conceptually awkward, MODFLOW won't notice anything strange unless the evapotranspiration package is activated separately from VFM. Why is surface topography data not used as the top of Layer 1?

Page 39, sixth para: It is also strange practice to use piezometric surfaces as the interface elevations. Is this technique used only where there is no physical layer, and dummy elevations are needed by MODFLOW?

Page 39, sixth para: Fig. 84 → Fig. 83.
Page 40, third para: Refer to Fig. 107.
Page 41, fifth para: Refer to Fig. 66 for the Parmelia Sand Member.

5.3 Model boundaries

Page 42, fifth para: Vol. I conflicts with Vol. III for constant head at the coast – zero vs 0.5 m AHD.
Page 42, seventh para: It is not clear where the no-flow boundary changes to constant head.
Page 42, last para: Refer to Fig. 10.
Page 43, first para: The use of the HFB package for faults is noted here, but there is no mention of its use in Vol. III; if used, what parameters were assumed? Any sensitivity analysis?

5.5 Hydrological processes

Page 44, fourth para: Clarify that the evapotranspiration package in MODFLOW is superseded by VFM. Clarify whether there is a standalone version of PRAMS that excludes VFM and uses conventional RCH and EVT packages.
Page 45: Section 5.5.2 gives the impression that MODFLOW's EVT package is still in play.
Page 45, second last para: How was the baseflow portion estimated? There is uncertainty here.
Page 46: After discussing losing and gaining streams, it is stated that only the drain package is used. Why not the river package?
Page 46, sixth para: Clarify that lakes are not fixed heads, but responsive to VFM recharge and evaporation.
Page 47, second last para: How many private licences now? (15 500?)
Page 48, last para: Clarify if the current model uses 3% growth or a scaling file.

6.2 Limitations of the model

Page 53: Misspelling of "gaps" in 6.2.4 header.
Page 53, last line of second para: allocation → usage.
Page 54, fourth para: are, is → should be;
Page 54, last para: hysraulic → hydraulic; qaulity → quality.

Figures

Figure 1: Should show rainfall with a smaller contour interval; the VFM report has Perth Airport average rainfall as 750 mm, here it is about 850 mm.

Figure 78: What is a "groundwater col"?

Figure 85: No contours are shown to the north (Mirrabooka).

Figure 116: Where are the horizontal barriers? Vol. III needs a similar figure.

Figure 119: No time scale units. Figure 139: What are the red symbols?

Figure 140: fradient → gradient.

Appendix 2 Amendments to Document #2

Executive summary

Page iii: geological and the some → geology and some

Page iv: localize → localized; tend to influenced → tend to be influenced.

Use of layer numbers is not useful in an Executive Summary; use formation names instead.

Similarly, reference to specific bores (e.g. AM6) is not useful without describing where it is.

Table of contents

Wrong page numbers after page 53.

Appendix E → Appendix D.

No water balance for Mirrabooka. Caption for Table D.3 is wrong in the appendix. Appendix D is omitted from the cover page of Volume III (third in set).

2 Modelling approach

Page 1, third para: to assessment → to assess.
Page 1, last para: Reference should be Middlemis et al. (2000); not in reference list.

3 Model construction

Page 3, fifth para: MOFLOW → MODFLOW.
Page 8, first para: It is stated that hi-res topographic data are used to define the top of layer 1, yet the previous page and Vol. I talk of the top being set at some water table elevation. Does MODFLOW pass depth-to-water to VFM, or does VFM calculate it?
Page 10: land use code → land use codes; the two VFM reports plus this report all have different numbers of land use codes. [It is time to rationalise the classification system.]
Page 11: Canci (2003) is not in the reference list.
Page 11, fourth para: soil profiles → soil profile.
Page 11, fifth para: are consider → are considered.
Page 11, fifth para: improve waters → improve water levels.
Page 11, fifth para: Xu et al. (2003) not in the reference list.
Page 12, first para: CSIRO (2002) not in the reference list.
Page 13, first line: MOSFLOW → MODFLOW.
Page 13, first para: Anderson (1997) not in the reference list.

Page 13, second para: Is the HFB package being used for faults?
Page 13, second last para: This refers to Figure 1 for implemented drains, but there are thousands there; it is not clear where drain cells have been placed in the model. The main drainages are not marked on Figure 1. See Fig. 116 in Vol. I.
Page 14, second para: drain conductance seems very high; they will act the same as constant heads.
Page 15, second para: While MODFLOW will report the net recharge determined by VFM, it cannot split off the ET component; is the VFM set up to do this accounting?
Page 15, second para: Daily recharge is said to be aggregated over the MODFLOW stress period; companion reports talk of the (shorter) time step as the aggregation period.
Page 15, Section 3.7: Say what the relative portions are for the three abstraction types.
Page 16, usage algorithm: Is the reported individual bore abstraction rate honoured? There seems to be an aggregation phase followed by a disaggregation phase, and I can't see why this is necessary.
Page 16, Table 3-6: Add 2004; are these calendar years? Figure 3: No units are given. Use sensible units to avoid labels having 9 digits. Looks like litres (cumulative?), or litres/year?
Page 18, first para: Clarify whether it is a property or a bore that receives an allocation. Refer to Figure 4.
Page 18, second para: How close does the synthetic abstraction get to full allocation? Can it go too far with a built-in scale factor?
Page 19, first para (after dot points): Is turf cycle used for all land uses? Is this sufficiently representative?
Page 19, second para: in consistent → is consistent; swan → Swan.
Page 19, last para: Acknowledges some error in ignoring irrigation from deep aquifers; this could go in the WEL package; is the RCH package still available for use, or will it be in conflict with VFM?
Page 20, Table 3-7: Add 2004. Page 23, Table 3-8: Add 2002. Add a table that compares the water volumes for the three abstraction types for the latest year.
Page 24, Figure 5: What are the units?

4 Model calibration

Page 26, third last para: 1989 → 1979.
Page 27, third para: Table 3-1 → Table 3-2.
Page 27, fourth para: at the bores ⇨ at which the bores.
Page 30, Figure 7: The legend values are not inclusive, e.g. 1-2, 3-4, …; which is 2-3? Clarify the polarity definition. Better to use white for 0 ± 1 m. Instead of a snapshot (Oct. 1992), the average error from Appendix C would be more diagnostic of overall performance.
Page 31, second para: Offsets can be due to initial conditions or hydraulic conductivity.
Page 31, fourth para: Describe where GB20 is.
Page 34, first para: mode → model.
Page 34, second para: There are 6 other bores with error > 5 m.

Page 36: Describe where specific bores are. Also pages 37, 39, 50.
Page 36, last para: though → thought.
Page 39, first para: compared → compared; AM68 → AM69.
Page 39, fifth para: The strong seasonal amplitude is diagnostic of the wrong S value rather than abstraction. Page 40, first para: a unique → unique. Page 40, third para: view → viewing; Table 4-3 → Table 4-2. Refer to Table 4-1 calibration statistics. Page 40, fourth para: increase → increased. Page 41, first para: These → The; In Table 4-2, report only one decimal place.

5 Water balance

Page 42, last para: Refer to land use codes in Table 3-3.
Page 43, Table 5-1: This table has no headers. The one header for recharge has the wrong label – it is not %. Add another column to describe the land use.
Page 44, first para: Xu et al. → Xu et al.
Page 44, Section 5.2: There should be summaries of the water balances for the groundwater sub areas.
The headers in the Appendix D tables are missing. Comment if any areas have an over-allocation problem. Highlight in tables.

6 Sensitivity analysis

Page 44, fifth para: quantifying → quantify.
Page 45, dot point 5: observations → observation.
Page 45, dot point 6: measure heads → measured heads.
Page 46, first para: The sensitivity coefficients in Table 6-2 require explanation; Tables 6.2 → Table 6-2.
Page 47, Table 6-2: Incomplete; replace colours by defined shading.
Page 47, second para: relative → relative to.

7 Conclusions

Page 49, last para: geological and the some → geology and some; localize → localized; influenced → be influenced.

8 References

Not sorted. Missing a few. CSIRO reports are incomplete citations (e.g. Silberstein).

Appendices

Location plans have corrupted bore symbols and north points. Figures C1-C4.
Appendix D missing from cover page.
Tables D.1-D.3 have incomplete headers.
Table D.3: Superficial → Yarragadee.
Add table for Mirrabooka.

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