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

Perth Regional Aquifer Modelling System (PRAMS) model development: Review of the Vertical Flux Component of the Perth Regional Aquifer Modelling System

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June 2009

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Cover photo: Lake Joondalup, Yellagonga Regional Park, July 2005 (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. Recharge is calculated by a Vertical Flux Model (VFM) that has been developed by CSIRO under contract to the Water Corporation (WC). It is coupled to a MODFLOW model that simulates saturated groundwater flow. This has been developed by CyMod Systems under contract to the Water and Rivers Commission (WRC).

This report provides a peer review of the vertical flux component of PRAMS. The Australian groundwater flow modelling guidelines are used to assess Part 1 and Part 2 reports that give an overview of the VFM model (Part 1), and detail on the application and useful outputs of the model (Part 2). This review does not delve into the rigour of the algorithms of the VFM model, as that is beyond the scope of work. Rather, it focuses on whether the VFM is appropriate as the recharge calculator for the MODFLOW model.

The review finds that there are many uncertainties in using the VFM to calculate recharge. These can be reduced by using the VFM in coupled rather than standalone mode, as the calculated recharge must be sufficient to explain the accretions to the water table that are measured in groundwater hydrographs. Too many alternative recharge algorithms do not seek this level of validation. Matching groundwater hydrographs necessarily involves a few aquifer properties as well, so it will never be possible to reach a unique solution.

The main virtue of the VFM model is that it is process-based. For this reason alone it is superior to alternative approaches. The model allows exploration of an array of land use scenarios and quantification of water balance components when coupled with a MODFLOW model. The Part 2 report gives a good illustration of the wealth of useful recharge information that can be derived, such as: spatial recharge distribution maps, time series recharge, partitioning of the water budget between consumptive processes, and recharge efficiency for different land use and vegetation types. Even though the absolute magnitudes might be uncertain, the relativities will be instructive for land use / vegetation scenarios.

Sufficient evidence is presented to show that the recharge estimates are of the right order, and relative behaviours are plausible. When expressed in terms of percentage rainfall, the possible errors are likely to be somewhat greater than 5%. Sensitivity analysis has shown that the most important parameters that require accurate quantification are rainfall, leaf area index (LAI), and light extinction coefficient. At this time, the use of only five climate zones means that the rainfall input to a MODFLOW cell could be in error substantially (by as much as 15–20%). This appears to be the major problem at the moment. It has resulted from the need to reduce runtimes for the coupled model by working with Representative Recharge Units (RRUs) that take into account a finite number of land use / vegetation, climate, soil and water table

depth combinations. There is also uncertainty in satellite-derived LAI estimates, the second most important parameter.

The VFM has been instructive in showing a low sensitivity of recharge to depth to water table, except for very shallow water tables within a few metres of ground surface. This substantiates the common use of much simpler recharge algorithms based on percentage rainfall with some threshold for antecedent moisture conditions, supplemented by an evapotranspiration algorithm for near-surface groundwater discharge.

This review is critical of the coarse zonation for the climate zones in defining RRUs. It is recognised that finer classification will amplify the number of RRUs and will make real-time simulation unreasonably slow. Hence, the idea of lookup tables should be revisited. This would require a lot of computing time initially to set up the tables, but after that the coupled simulations would be fast and it should be possible to get down towards cell scale resolution (say, 1 km).

1 Introduction

This report provides a peer review of the Vertical Flux Model (VFM) component 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 VFM model has been developed by CSIRO under contract to the Water Corporation (WC). The saturated flow component of the PRAMS model has been developed by CyMod Systems under contract to the Water and Rivers Commission (WRC). 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

Where relevant, the 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. Not all questions in the checklists are pertinent to a site-specific model.

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.

The guidelines pertain to a groundwater flow model, and are appropriate for the saturated groundwater flow component of the PRAMS model. They are less applicable to the VFM recharge component of the model. In this review of the VFM model, only the Report checklist is used unchanged, but qualitative commentary provides supplementary assessment. A full peer review of the groundwater flow component of the study can be found in a companion report (Merrick, 2005b).

4 Evidentiary basis

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

1. *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.*

2. *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.*

3. *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.*

4. *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:

5. *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.*

6. *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.)*

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 a number of clarification emails and 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.

In this section, peer review is limited to the VFM model as reported in Documents #1 and #2. These reports cover similar ground but have different authorship (CSIRO and WC). The first report is essentially an overview, while the second report gives a more detailed account of application. It is understood that the authors of Document #1 were requested to limit their report to an overview suitable for a non-specialist audience, with not much detail. The reviewer is aware of companion documents (Vertical Flux Model Operation Manual, Data Preparation Manual), but these have not been examined as part of this review. This review focuses on whether the VFM is appropriate as the recharge calculator for the MODFLOW model, not on the intrinsic capability of VFM for simulating biophysical relationships, or its value as a standalone system.

The peer review checklists are presented in Tables 1 and 2.

Table 1 Model review – The report: VFM model part 1 (CSIRO)

Q.	Question	Not applicable or unknown	Score 0	Score 1	Score 3	Score 5	Comment
1.1	Is a report provided?		No			**Yes**	
1.2	Are relevant prior or companion reports provided or accessible?		No		**Yes**		VFM Part 2 is provided. Operation Manual and Data Preparation Manual not provided.
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	Poor layout. Inserted figures and tables not merged with text.
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**		Complex biophysical processes.
1.8	Are model parameter distributions disclosed?		Missing	Deficient	Adequate	**Very good**	Tables 3, 4.
1.9	Are model parameter statistics reported (median, range, standard deviation)?		Missing	Deficient	**Adequate**	Very good	High and low values in Table 4.
1.10	Is it clear how stress datasets have been compiled?		Missing	Deficient	**Adequate**	Very good	Rain, ET.
1.11	Would it be possible to re-create the structure of the model from what is reported?	**N/A**		No	Maybe	Yes	
1.12	Is a water or mass balance reported?		Missing	Deficient	**Adequate**	Very good	By default, in quantifying recharge to WT; not aggregated for pilot study or MODFLOW model area.
1.13	Are recommendations reasonable and supported by evidence?		Missing	Deficient	**Adequate**	Very good	Mainly more research into processes.
1.14	Has the modelling study satisfied project objectives?		Missing	Deficient	**Adequate**	Very good	VFM has been built, tested, and coupled with MODFLOW model.
1.15	Are the model results of any practical use?			No	Maybe	**Yes**	Instructive sensitivities and relationship of gross recharge to rainfall. Still substantial uncertainty in the validity of recharge estimates.
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: VFM model part 2 (WC)

Q.	Question	Not applicable or unknown	Score 0	Score 1	Score 3	Score 5	Comment
1.1	Is a report provided?		No			Yes	
1.2	Are relevant prior or companion reports provided or accessible?		No		Yes		VFM Part 1 is provided. Operation Manual and Data Preparation Manual not provided.
1.3	Is it clear which person(s) did the modelling?		No		Yes		Initials only
1.4	Is the report well structured?			Deficient	Adequate	Very good	
1.5	Is the report presentation of acceptable quality?			Deficient	Adequate	Very good	
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		Complex biophysical processes.
1.8	Are model parameter distributions disclosed?		Missing	Deficient	Adequate	Very good	Several tables.
1.9	Are model parameter statistics reported (median, range, standard deviation)?		Missing	Deficient	Adequate	Very good	Ranges are given in Table 16 for most parameters.
1.10	Is it clear how stress datasets have been compiled?		Missing	Deficient	Adequate	Very good	Rain, ET.
1.11	Would it be possible to re-create the structure of the model from what is reported?	N/A		No	Maybe	Yes	
1.12	Is a water or mass balance reported?		Missing	Deficient	Adequate	Very good	For RRUs, model domain quarters, recharge maps, time series plots, probability function.
1.13	Are recommendations reasonable and supported by evidence?		Missing	Deficient	Adequate	Very good	
1.14	Has the modelling study satisfied project objectives?		Missing	Deficient	Adequate	Very good	Extensive exploration of VFM outputs, and verification of recharge estimates with literature.
1.15	Are the model results of any practical use?			No	Maybe	Yes	Initial probability function for recharge that can support risk-managed water allocation.
1.16	Has the modelling study been cost-effective?	Unknown		No	Maybe	Yes	Unknown to reviewer.
1.	**Total score**						

6 Discussion on Document #1

6.1 Overview

The Vertical Flux Model (VFM) essentially replaces the default recharge (RCH) and evapotranspiration (EVT) functions in MODFLOW. Both of these are handled very simply in MODFLOW.

The RCH package shifts the burden of estimation to the user, and MODFLOW requests only a volume of water to be dumped on the water table in each stress period. There is no allowance for interception and use of raw rainfall by vegetation, or of transition of infiltrating water through the soil zone. Modellers commonly estimate the rainfall recharge as a percentage of rainfall, sometimes lagged, and sometimes with a threshold to allow for antecedent moisture in the soil profile. This is the approach taken by the Department of Natural Resources in New South Wales.

The EVT package allows for discharge of water from a shallow water table, using a linear decay function with increasing water table depth. This package is used routinely by the Department of Natural Resources in New South Wales.

The default MODFLOW packages are usually sufficient for regional model calibration and quantification of the gross water budget for aquifer systems. However, they give little insight into the processes operating near-surface, and do not allow detailed scenario analysis for land use changes.

The virtue of the VFM model developed by CSIRO is that it is a process-based model that aims to replicate a host of biophysical processes that describe soil-vegetation-air interactions. It has the advantage of allowing the investigation of land use scenarios that can be articulated clearly. However, the performance of the model as reported in Document #1 is not reassuring, which suggests that the computed impacts of land use changes might not be any more accurate than a simpler algorithm for recharge estimation (Principle of Parsimony). The latter, however, does not offer a simple approach to specifying land use scenarios. For this reason, it is recommended that the VFM be retained in the PRAMS model, but users should not be lulled into believing that the results are inherently more accurate because the processes are modelled more realistically. Nevertheless, the relativities between alternative land use scenarios should be instructive.

Townley (2000) in Document #3 has written an excellent review of vertical flux modelling The VFM incorporates most of the wish-list items in that review, particularly physically-based processes, and time-varying land use. It honours the call for fine temporal resolution, but suffers from coarse spatial resolution by reliance on representative recharge units (RRUs). The Queensland Government Department of Natural Resources and Mines has also developed a vertical flux model, called SPLASH (Soil **PLA**nt Salinity and rec**H**arge) (Arunakumaren, 1997). It is not as physically based as the VFM. It is a lumped parameter model that aims to simulate moisture in the plant root zone and the underlying unsaturated zone. Excess water in the water balance is transmitted to the water table as deep drainage. The Richards Equation is replaced by a number of moisture stores with transfer rules. A runoff filter provides a threshold for effective rainfall infiltration. Unlike the VFM, crop growth is an important factor as crop yield is used for validation. The equivalent of a RRU is called a “case”, designated by a unique combination of soil type (~10), rainfall zone (~10), and land use / crop type (~4). Program STRESGEN converts the 1-D SPLASH results to case volumes for input to MODFLOW. The rainfall zonation is finer than that used in VFM for the PRAMS model. There is no real-time coupling with the MODFLOW model, and no dependence of estimated recharge on depth to the water table.

The VFM carries a heavy computational burden while it remains coupled in real time to the MODFLOW model. A re-think on lookup tables is recommended, together with more rainfall zones to give finer spatial resolution.

Following are comments on specific sections of the Part 1 Report (Document #1). The presentability of this report would be enhanced by embedding figures and tables in the correct locations within the text, without numerous page breaks. Primary and secondary section headings should be distinguishable, to give an obvious structure to the report. The reference list (pages 48–49) is incomplete; report numbers should be given, and CSIRO reports should be designated as such.

6.2 Model description (Section 3)

Page 5: Total recharge is said to pass to MODFLOW at the end of each time step; elsewhere, the aggregation is said to happen at the end of each stress period. This is stated in the Executive Summary in Document #1, in Document #2 (page 23), and in Document #6 (page 15). Clarification and consistency are required.

Representative Recharge Units (RRUs) are based on land use / vegetation (13 classes), climate (6 classes), soil type (6 classes), and depth to water table (8 Classes). There is no clear statement on the number of classes in the Part 1 report; they are specified in the Part 2 report. Document #6 (pages 10–12) has 14 land use classes and 5 climate classes. Clarification and consistency are required. The total number of RRU combinations should be reported.

This section of the report should stress that VFM is run in real time, coupled with MODFLOW, rather than using the alternative approach of lookup tables as MODFLOW is running.

Simpler non-WAVES recharge models are a good idea where management intervention usurps a biophysical process. The second recharge model has a sensible stepwise ET model, but there is no mention of its rainfall infiltration algorithm. Presumably, it is the same as the first non-WAVES model.

As VFM replaces the EVT module in MODFLOW, it appears that the RCH module is still available for use. It would be possible to use PEST with pilot point recharge distributions to get a pattern that explains the observed water table pattern and dynamics. This could be compared with VFM patterns and magnitudes to highlight where discrepancies exist, or to indicate if VFM produces a similar order of magnitude. Both approaches will have errors.

Editorial issues

Page 3, Line 1: repetition of sentence on lakes and wetlands.

6.3 Program operation (Section 4)

The stated land uses (page 7) do not elaborate on the sub-classes for pines, Banksia, and urban. A full list is appropriate.

6.4 Data collection (Section 5)

The restriction to 5 (or 6) climate classes is a concern. Any given zone can cover a wide range in actual rainfall depths. The nearest stations are only 10 km apart, but there is a gap of 120 km between stations across the central third of the PRAMS model area, a very large area. This has no representative climate station. This means that a model cell just to the west of the Zone 4 / Zone 5 boundary will be given the rainfall of the Perth Regional Office. The rainfall could in error by 15–20%, and that will swamp other uncertainties, given that rainfall is the primary determinant of recharge. This effect is illustrated in Figure 21 of the Part 2 report (Document #2), which shows the sensitivity of annual recharge to rainfall. Model cells with rain between 800 mm and 1100 mm will be given the rainfall of the nearest point, and hence the recharge of the nearest point. The real recharge should be interpolated between the endpoints. Either more climate zones are needed, or the rainfall has to be interpolated between climate stations.

Similarly, the inland town Gingin is given the same rainfall pattern as the coastal town Lancelin.

Table 2 (page 12) should state whether the coordinates are AMG or MGA. The average rainfall at Perth Airport is given as 750 mm, but Document #5 has about 850 mm.

A simple definition of Leaf Area Index (LAI) should be presented.

Editorial issues

Page 17, Line 3: Is Silberstein et al. 2003 or 2002? Adjust reference list.

Table 4 (pages 24-25) has poor horizontal alignment of values.

6.5 Sensitivity analysis (Section 6)

The first example in Section 6.1 is not a sensitivity analysis, and should properly appear in a Verification section. It shows in Figure 8 the relationship between modelled recharge and estimated recharge for seven sites or events. [The original figure in the report was illegible and was replaced on request; the new figure shows a different relationship.] While the agreement is said to be "reasonable", it is clear that the differences are substantial and are in the order of 30%. Inadequate background is given for this comparison. Are the measurements all on the same soil type, for the same vegetation? The reference work is Salama et al. (1998) in the text and Salama et al. (2000) in the substituted figure. Neither is in the reference list, but there is an entry for Salama et al. (1999).

Table 5 (page 29) gives a useful and plausible sensitivity matrix that shows the variation of recharge to depth to water table, LAI and vegetation. The table would be more informative if expressed as a percentage of rainfall, or as a normalised sensitivity coefficient to draw out the relative importance of parameters.

For a non-specialist audience, Figures 9 and 10 must leave a lot of confusion. They show measured ET versus water table depth (Figure 9) and LAI versus water table depth (Figure 10). The authors seem to be using the figures to demonstrate the expected link between LAI and water use, but the graphs look nothing like each other, although one is said to "corroborate" the other. Figure 9 suggests that ET does not depend on depth to water table; Figure 10 suggests a mild dependence.

Reference is made in Section 6.2 to a number of bores, PM4 etc. Where are they? Measured and simulated soil moisture profiles are given in Figure 11 for the period May to October 2002. The rainfall during this time should be reported. The depth scales of the graphs are not aligned properly, and there is no explanation of the vertical distribution of Ksat values. This reviewer finds the poor agreement between the two alarming rather than consoling. Surely PEST could have been used to get better calibrations. The moisture contents are in serious error, and this brings into question the validity of associated recharge estimates. While the wetting fronts show roughly the right behaviour, the simulated front is about 60% too fast.

Section 6.3 (page 36 and Figure 12) shows correlations between simulated recharge and annual rainfall for shallow (6 m) and deep (15 m) water tables. These results are encouraging. They show that rainfall provides the dominant control on recharge, and help to support the alternative use of simpler recharge algorithms. The correlations show that allowance must be made for (antecedent) thresholds. The formulas for groundwater recharge (GR) could be reformulated in the form:

GR = coefficient * (Rain – Threshold)

When this is done, the thresholds for the three examples become 550 mm, 480 mm, and 594 mm. It is instructive to express the recharge as a percentage of rainfall, as shown in the following Table 3. Except for very low rainfall, there is not much difference between the figures. This supports only a minor role for water table depth as a factor in recharge.

Table 3 Recharge as a Percentage of Rainfall

Rain (mm)	**WT at 6 m**	**WT at 15 m Med-high rain**	**WT at 15 m Long-term rain**
1000	36%	31%	35%
800	25%	24%	22%
700	17%	19%	13%
600	7%	12%	1%

The same lack of sensitivity to water table depth is expressed in Figure 13, except for very shallow water tables (less than 4 metres). This supports the normal practice of using the EVT package to reduce net recharge when the water table lies within the top few metres of the soil profile.

Table 6 (page 43) shows that the choice of root decay algorithm can cause a significant recharge error in the order of 5%.

Table 7 (page 44) is a useful summary of sensitivities, expressed as percentage changes in recharge. This shows high sensitivity to LAI (14%) and light extinction coefficient (12%); moderate sensitivity to rooting depth (8%), carbon assimilation rate (6%), conductance slope (6%); and mild sensitivity to soil holding capacity (4%), interception (3%), and Ksat (2%). Hence, taking into account the large number of parameters in the VFM code, there must be significant uncertainty in VFM recharge estimates.

Editorial issues

Page 31, Line 23: Farrington et al. → Farrington and Bartle.

Page 36, Line 19: the formula for GR in the text does not match the one in Figure 12.

Page 41, second last line: then 12 m → than 12 m.

6.6 Pilot study (Section 7)

The report would have benefitted from a brief summary of the results of the pilot study, or reference to the Part 2 report. The only reference is to CyMod (2003) which was not available to this reviewer. Hence, the reviewer does not know if the VFM performed well or not, and has to settle for an assurance that “the coupled model represents relevant conditions on the Swan Coastal Plain to an acceptable level”.

6.7 Conclusions (Section 8)

The authors state that “the model performs very well in reproducing field measurements”. If it does, it has not been demonstrated in this report.

The authors also state the need for good estimates of water balances or there will be “no real test of the model’s performance”. This is true. It surprises this reviewer that so little relevant information seems to have resulted from many decades of work on the Gnangara Mound.

7 Discussion on Document #2

7.1 Overview

This report is of a much higher quality than the Part 1 report. There is a very good introductory section on conceptualisation of the processes within the VFM model.

This report gives more evidence and more reassurance that the VFM is performing well, although the uncertainty in recharge estimates of 5–7% seems a little ambitious, given the large numbers of model parameters carrying their own levels of uncertainty. The summarised recharge as percentages of rainfall for each land use class (on page vii) shows plausible values ranging from zero (medium-high density pine) to 63% (urban – commercial/industrial). The long-term average over the whole model domain is said to be 18% (page vi). Comparative measurements are provided in a literature review (pages 3–4).

Following are comments on specific sections of the Part 2 Report. The figures in this report are missing scales, north points and eastings/northings.

7.2 Conceptual model (Section 2.3)

In Section 2.3.5.1, in reference to the five chosen climatic zones, it is stated that the "variation in climatic characteristics within each zone are considered to be relatively small". This reviewer has already expounded on this shortcoming in Section 6.4, where he has argued that the error could be as much as 15–20%, and that will swamp other uncertainties given that rainfall is the primary determinant of recharge.

The vertical accuracy of the Digital Elevation Model (DEM) is recognised (page 13) as a source of error. It is said to be 2.0 m here, but the Part 1 report has 1 m (page 10). The recharge can be in error significantly only for very shallow water tables, as the Part 1 report shows a very mild dependence of recharge on depth to water table. The accuracy of the recharge estimate also depends on how well the MODFLOW model replicates the amplitude of seasonal water tables. This reviewer has noted that some areas require adjustment of specific yield to match the amplitudes better (Merrick, 2005b), but there is insufficient information in the reports to know if these areas have water tables close to ground surface.

Editorial issues

Page 13, Line 12: Delete Table 1–2.

7.3 VFM Recharge models (Section 2.4.2)

Reference is made to work by Zhang et al. (1996, 1999) which shows that WAVES (a component of VFM) has correctly simulated water dynamics and vegetation growth for a range of conditions (page 18).

Verification of WAVES refers to three studies (page 19), but little is given in the way of results. The reader is referred to the Part 1 report, but this covered only one of the studies and did not show good performance.

Editorial issues

Page 19, fifth last line: 3 → Table 3. Also page 35.

7.4 Pilot study (Section 2.7)

The Pilot Study was undertaken around the Lexia borefield using a sub-model of PRAMS 2.1, and the VFM model was subsequently coupled with PRAMS 3.0 for the whole model domain. This highlighted a number of issues discussed on pages 24 to 28. The VFM was unable to handle dense pines over a shallow water table. To solve the problem, a dynamic root depth algorithm was added and extra pine classes were introduced. Water tables above ground level in the Guildford soil required use of an artificially low hydraulic conductivity (0.01 m/day); this is still an area of concern. Excessive recharge north of Pinjar required the introduction of extra Banksia classes, and highlighted the uncertainty in satellite-derived LAI values. Coffee rock might also be a causative factor here. To correct high-amplitude groundwater hydrographs, Ksat was reduced in the VFM model for two soil types. It would have been better to adjust specific yield in the MODFLOW model (Merrick, 2005b)..

Editorial issues

Page 25, para 2: Delete “become”.

7.5 Plot scale simulation (Section 4.1)

A decoupled PRAMS run was made to give a detailed water balance for each RRU. Mention is made of modifications to the MODFLOW BAS file, which apparently (from email clarification) is simply a workaround to achieve decoupling. It would be better to delete any mention of MODFLOW in this circumstance.

Figures 18 and 20 demonstrate the insensitivity of recharge to water tables deeper than 4 metres. This supports results in the Part 1 report.

Figure 21 is very important as it shows the sensitivity of annual recharge to rainfall. As mentioned in Section 6.4, model cells with rain between 800 mm and 1100 mm will be given the rainfall of the nearest point, and hence the recharge of the nearest point. The real recharge should be interpolated between the endpoints.

A thorough water balance is presented in Figure 19 for different land uses and VFM processes. These results are aggregated to four zones covering the model domain, plus a sub-zone for Gnangara, to give time series recharge (GL/year) from 1986 to 2003 (Figures 24, 26). This is very informative but would benefit from comparison with rainfall residual mass (cumulative deviation from the mean, CDFM). One would expect the graphs to have the same shape. If they do, this would corroborate the gross performance of the VFM model.

Figure 29 is an important and innovative diagram. It shows the probability of annual recharge on the Gnangara Mound, and allows a risk management approach to water allocation. It is the same concept that was developed by Merrick (2000) who quantified the uncertainty in aquifer sustainable yield from MODFLOW water budget outputs. As Figure 29 is derived from Figure 28, which shows a lot of scatter, it is recommended that a relationship be pursued between average recharge and rainfall residual mass. Less scatter should result. The probability function in Figure 29 could be compared with a similar probability function for annual rainfall. Do they have the same shape?

The areal recharge maps (Figures 30, 31) when compared with Figure 6 seem to show some edge effects in Zones 3, 4 and 5 due to coarse climate zonation.

7.6 Sensitivity and uncertainty analysis (Section 5)

A thorough sensitivity analysis was conducted on 19 parameters for typical RRU units (low and medium density Banksia woodland). Depth to water table was found to be unimportant.

For medium Banksia with 10% perturbations in parameters, the sensitivity analysis shows high sensitivity to rainfall (51%), LAI (22%), light extinction coefficient (18%) and rooting depth (18%); moderate sensitivity to carbon assimilation rate (10%) and conductance slope (10%); and mild sensitivity to interception (6%) and soil holding capacity (5%). These results are very similar in ranking to the sensitivity analysis reported in the Part 1 report (see Section 6.3 of this review).

A sensitivity analysis was run also for 5 years with the full PRAMS model. For the northern area, by way of example, this shows high sensitivity to rainfall (31%), LAI (11%) and light extinction coefficient (10%); moderate sensitivity to carbon assimilation rate (5%); and mild sensitivity to soil holding capacity (4%), hydraulic conductivity (3%), and rooting depth (2%). Not all parameters were perturbed by 10%, and not all parameters were trialled. Nevertheless, the ranking of important parameters is consistent.

A rigorous uncertainty analysis was conducted using the First Order Second Moment (FOSM) method. Its basis is explained simply. Essentially, the method rests on the aggregation of Jacobians (partial derivatives) of recharge increments for each perturbed parameter. It should be noted that this approach ignores interaction effects between parameters.

For medium Banksia, the results of the FOSM analysis suggest high sensitivity to carbon assimilation rate (20%), LAI (20%), rooting depth (19%) and soil holding capacity (11%); moderate sensitivity to interception (8%), light extinction coefficient (8%), and hydraulic conductivity (8%); and mild sensitivity to litter (3%) and conductance slope (2%). Rainfall was ignored, as it was "considered to be low as the data is sourced from the BoM". While the error is negligible at a climate station, it is not negligible at a MODFLOW cell. Figure 21 has been used to show that errors up to 15–20% can result from coarse climate zonation. The analysis should have included rainfall with a variance derived from the difference in rainfall between neighbouring climate stations.

Ignoring rainfall error, the FOSM analysis suggests a recharge of 38%–5% for low density Banksia, and 18% ± 7% for medium density Banksia.

However, this reviewer has desk-checked a few calculations of FOV using equation (7) and cannot reproduce the values listed in Table 16. For soil water holding capacity, this reviewer calculates 5% (low Banksia) and 22% (medium Banksia), compared with reported values 16% (low Banksia) and 11% (medium Banksia). For a given parameter, such as soil water holding capacity, with fixed values for Δx, σ_x and σ_R, we expect:

$$FOV_X \alpha \ (\Delta F)^2$$

Table 15 shows that the absolute value of F (change in recharge) is less for low Banksia than for medium Banksia. Hence, FOV must be less for low Banksia than for medium Banksia. However, Table 16 has them reversed.

Editorial issues

Page 46, Table 15: It is unlikely that carbon assimilation and conductance slope would give identical changes in recharge.

Page 48, Table 16: For soil holding capacity, delete "%" and let 3 → 0.03.

8 Recommendations

The main virtue of the VFM model is that it is process-based. Although there are uncertainties inherent in this approach, given the incorporation of so many parameters, the model allows exploration of an array of land use scenarios and quantification of water balance components when coupled with a MODFLOW model. The VFM could operate in standalone mode, but validation of groundwater hydrographs is essential to tie down some of the uncertainty in the recharge estimation.

The Part 1 report did not do justice to the credibility of the VFM algorithms. The Part 2 report is much more reassuring, and provides evidence that the recharge estimates are at least in the right ballpark, and the relativities between different combinations of conditions are plausible. Some very interesting post-model work has been reported in the Part 2 report by examination of predicted recharge distributions in space and time, and expression of recharge as a probability function (at least for the Gnangara Mound). This is the direction that estimates of aquifer sustainable yield should be heading, by admitting that the estimates will always be imprecise and encouraging a risk management approach to water allocation.

This review has been critical of the coarse zonation for the climate zones in defining Representative Recharge Units (RRUs). It is recognised that finer classification will amplify the number of RRUs and will make real-time simulation unreasonably slow. Hence, the idea of lookup tables should be revisited. This would require a lot of computing time initially to set up the tables, but after that the coupled simulations would be fast and it should be possible to get down towards cell scale resolution (say, 1 km).

It is likely that the uncertainty analysis reported in Part 2 has overstated the accuracy of recharge estimates, said to be in the order of 5%–7% (Banksia woodland).

The following recommendations are made:

- That the FOSM uncertainty analysis calculations be checked
- That rainfall be included in the FOSM uncertainty analysis
- That the time series recharge graphs from 1986 to 2003 (Figures 24, 26 in Part 2) be compared with the rainfall residual mass (cumulative deviation from the mean, CDFM) graph; similar shapes would corroborate the gross performance of the VFM model
- That a relationship be pursued between average recharge and rainfall residual mass, similar to Figure 28 (Part 2), and that the probability function for annual rainfall be compared with Figure 29 (Part 2)
- That consideration be given to the practicality of replacing real-time VFM simulation with table lookups at the end of each MODFLOW stress period

- That efforts be made to improve estimation of the most sensitive parameters in the VFM model: cell rainfall, leaf area index (LAI), and light extinction coefficient
- That the VFM model be retained and supported as the recharge calculator for the coupled PRAMS model.

9 References

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