Groundwater Modelling Guidelines for Australia: An Overview

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Abstract: Management strategies for resource allocation and control of resource degradation are increasingly dependent on the credibility of models. In a project sponsored by the Murray-Darling Basin Commission (MDBC), best practice guidelines have been developed for application to groundwater flow modelling projects. The project was undertaken to address concerns, often from community groups, about the consistency and suitability of modelling methodologies being applied to a range of natural resource management projects. This paper presents an overview of the guidelines, and a companion paper discusses detailed model review methodologies. The guidelines are designed to encourage consistency and transparency in model development, and to provide guidance to modellers and end-users to assess whether models are fit for purpose, calibrated to agreed targets, and adequately documented and reviewed. A model study brief structure is also presented in the guideline to help with scoping modelling studies. Solute transport simulation and unsaturated zone modelling are not within the scope of this guide. Compliance with the guidelines will encourage best practice and reduce the level of uncertainty for decision-makers relying on model results. A national workshop process was undertaken to review the draft guide, and achieve consensus regarding practical and implementable guidelines. Consultants, government agencies, academics, and community representatives from rural and regional Australia provided workshop input. These best practice guidelines are being considered by the Agriculture and Resource Management Council of Australia and New Zealand (ARMCANZ) for national adoption, and the Murray-Darling Basin Commission is developing a plain English communications document for broad distribution.

Keywords: Groundwater; Guidelines; Modelling

1. INTRODUCTION

Best practice guidelines have been developed for managing and undertaking groundwater flow modelling projects in Australia [Middlemis et al., 2000]. The guidelines were developed for the Murray-Darling Basin Commission (MDBC) for application within the Basin, but the recommended approaches are suitable for flow modelling projects generally. To that end, the guidelines are being considered by the Agriculture and Resource Management Council of Australia and New Zealand (ARMCANZ). for national adoption. In order to promulgate the guidelines for widespread adoption, MDBC is planning a print run of 500 to 1000 copies of the 169-page technical document, and 5000 copies of a 20-page plain English summary. The guidelines are also accessible on the MDBC web site (www.mdbc.gov.au).

The driving force behind the development of the guidelines was a perception amongst end-users of model studies in the Murray-Darling Basin that model capabilities had been "over-sold". There was also a lack of consistency in approaches, communication and understanding among and between modellers and end-users, which often resulted in considerable uncertainty for decision-making on resource management.

The decision-making uncertainty applies at all stages throughout model studies:

- at the initiation of a modelling study, when objectives and study purpose may be poorly considered or specified, or data availability, integrity and reliability are uncertain;

- during the study, when poor communication may result in models being developed that are not fit for purpose;
- at the end of a study, when the modelling results may not be well presented to, or understood by, clients.

There was perceived to be a need for guidelines to reduce the level of uncertainty for model study clientele, including resource management decision makers and the community, by promoting transparency in modelling methodologies and encouraging consistency and best practice. Guidance is needed also for non-specialist clientele to outline the steps involved in scoping, managing and evaluating the results of groundwater modelling studies. In addition, modelling specialists will benefit from guidance on the technical standards expected to be achieved for a range of project scopes.

A national workshop was held to review the draft guide, and achieve consensus regarding practical and implementable guidelines. The guide is designed to be applied with flexibility to simple, small scale, small budget groundwater flow modelling jobs, as well as much larger and more complex regional modelling studies with substantial resource management implications.

The guidelines are to be applied to new groundwater flow modelling studies and reviews of existing models. Solute transport and unsaturated zone modelling were not within the scope of this project. Some specialised aspects are also not addressed comprehensively in the guide, notably detailed methodologies for dealing with recharge, evapotranspiration from shallow water tables, and associated links between agricultural activity and these processes, although general aspects are addressed.

The guide should be viewed as a reference point for framing modelling projects, developing appropriate models, and assessing model performance. The intention is not to provide a prescriptive step-by-step routine, as the site-specific nature of each modelling study renders this impossible, but to provide overall guidance and to de-mystify the complexities of the modelling process. The guide offers an organised collection of options and does not recommend a rigid course of action. The guide must be used in conjunction with experienced professional judgment, and it does not replace the standard or duty of care of professional service.

2. BEST PRACTICE

2.1 Literature Review

There are very few published and accepted guidelines on groundwater flow modelling, and none in Australia prior to this study. The notable international example is the suite of Standard Guides from the American Society for Testing and Materials (ASTM), which are reasonably well-accepted standard practice guidelines [Ritchey and Rumbaugh, 1996]. The American standards development process commenced in 1989, with the first two standards issued in 1991 [Ritchey and Rumbaugh, 1996]. Additional standards have ensued on various aspects of groundwater modelling. The ASTM guides are reviewed at least every five years under a consensus process and therefore carry some weight, although the process involves only technical experts and not the community.

The US Army Corps of Engineers Manual [USACE, 1999] is more applicable to a broader audience, as it is more descriptive in nature but refers to the detailed ASTM protocols. The manual outlines the steps in an overall groundwater investigation and modelling study, and provides very useful background on this aspect (www.earthwardconsulting.com/library).

There is a draft UK document which is highly technical and intended for use by experienced modelling professionals within the Environment Agency on large-budget regional modelling consultancy projects [UKEA, 1999].

Another draft document for The Netherlands [Rijkswaterstaat, 2000] provides a handbook for good modelling practice. It aims primarily at supporting the modeller, and has a particularly good discussion of pitfalls in modelling.

The ASTM guides, and most other guideline documents issued in other countries, including most text books, are intended for application to solute transport modelling as well as groundwater resource (flow) modelling studies. They are usually technical in nature, and not as "down to earth" as those designed for Australian conditions.

2.2 Methodology

The literature review identified the following strategic approach for achieving modelling study best practice, which has been used to design the guidelines:

- The model study objectives and the model complexity required should be stated clearly at the outset.
- A level of complexity should be adopted that is high enough to meet the objective, but low enough to allow conservatism where needed.
- A conceptual model should be developed that is consistent with available information and the project objective.
- If possible, a site visit should be undertaken by an experienced hydrogeologist /modeller at the conceptualisation stage.
- Model development should be undertaken in three main stages, with a check point for reporting and review at the end of each stage:
  - Conceptualisation
  - Calibration and verification
  - Prediction.
- The non-uniqueness problem should be addressed by using measured hydraulic properties in the model, and calibrating to data sets collected from multiple distinct hydrologic conditions (if possible).
- An assessment of model uncertainty should be performed by undertaking application verification, and sensitivity or uncertainty analysis of calibration and prediction simulations, as appropriate for the study.
- Adequate documentation of the model development and predictions is required.
- Peer review of the model should be undertaken at various stages throughout its development, and to a level of detail appropriate for the model study scope and objectives.
- Effective communication has to be maintained between all parties involved in the modelling study through regular progress reporting (technical issues and project management) and review.

2.3 Conceptualisation

The definition of the study objectives, the model complexity, and the development of an adequate conceptual model are the vital first steps in a modelling programme. A conceptual model is a simplified representation of the key features of the physical system, and its hydrological behaviour. It forms the basis for a site-specific computer model, but is itself subject to some simplifying assumptions. The assumptions are required partly because a complete reconstruction of the field system is not feasible, and partly because there is rarely sufficient data to completely describe the system in full detail.

The conceptual model should be developed using the *principle of parsimony,* also known as Ockham's Razor which dates from the early 14th Century - *"Entia non sunt multiplicanda sine necessitate".* This may be translated literally as "The number of entities should not be increased without good reason", or loosely as "It is vain to do with more what can be done with fewer" [Constable et al., 1987]. In other words, the model should be kept as simple as possible, while retaining sufficient complexity to adequately represent the physical elements of the system, and to reproduce hydrological behaviour.

However, the model features must be designed so that it is possible for the model to predict system responses that range from desired to undesired outcomes. In other words, the model must not be configured or constrained such that it artificially produces a restricted range of prediction outcomes.

2.4 Model Complexity

The introductory ASTM guide (D5880) introduces the term *model fidelity*, with the scale from low to high fidelity being borrowed from the audio electronics field. The term is meant to define the degree to which a model application resembles, or is designed to resemble, the physical hydrogeological system. The Australian guidelines prefer the term *model complexity*, to avoid the inference that one level of model is better than another. A high complexity model is not necessarily better than a low complexity model. In many cases, a low complexity model will be more appropriate for the model purpose, for the data availability, and for the limited resources available for the project. The community representatives at the workshop found the term "complexity" more meaningful than "fidelity.

The Australian guide classifies models as "Simple", "Impact Assessment" and "Aquifer Simulator" models, in order of increasing complexity. The equivalent terms in the ASTM guide are "Screening", "Engineering Calculation" and "Aquifer Simulator" models. The study purpose and objectives must be carefully considered and clearly stated at the outset of any modelling study in order to develop an adequate tool with the appropriate level of complexity.

A *Simple* model has low complexity. It is appropriate for a simple groundwater system, an aquifer with little data, a feasibility study, or a preliminary assessment, and will usually employ an analytical or semi-analytical technique.

An *Impact Assessment* model has moderate complexity. It is appropriate for solving a site-specific problem, for predicting the impacts of a proposed development, will often employ conservative or equilibrium assumptions, and could use either an analytical or numerical technique.

An *Aquifer Simulator* model has high complexity. It is appropriate for a complex groundwater system which recognises spatial variability, system dynamics, and interactions between processes. It will be suitable for predicting the response of an aquifer system to arbitrary changes in hydrologic conditions, and will normally require numerical solution.

3. GUIDELINES

3.1 Introduction

In all, there are 67 guidelines within 27 categories. Several guidelines have been paraphrased in the preceding sections, and a selection will be given below. The major themes addressed by guidelines are:

- Modelling best practice.
- Objectives, complexity, data collation, units.
- Conceptual model, code selection.
- Model study plan.
- Model construction, initial conditions, calibration, non-uniqueness, performance measures, verification.
- Prediction, sensitivity analysis, uncertainty analysis.
- Reporting, archiving.
- Review, audit.

3.2 Model Study Plan

Guideline 2.6:

"A Model Study Plan should be completed and reviewed at the end of the Conceptualisation stage with a report that includes details of the:

- *study purpose, objectives, model complexity, and resources required to complete the study;*
- *initial hydrogeological interpretation and conceptual model, data summary, boundary conditions and preliminary water budget;*
- *selected modelling code and limitations/uncertainties in the modelling approach;*
- *model design and configuration specifics, including details on the boundaries; grid; layers; aquifer units and parameters; recharge, discharge and water balance; surface-groundwater interaction; calibration and prediction timeframes and accuracy targets; steady state or transient calibration and/or prediction runs; and data available and required to complete the study;*
- *for high complexity models, it may be appropriate to document the data collated by presenting the database in the Model Study Plan report (e.g. in tables or appendices, or possibly on a CD for archive purposes)."*

3.3 Calibration and Verification

The guide recommends that the success of model calibration should be evaluated in both quantitative (statistical) and qualitative (pattern-matching) terms, to evaluate the degree of correspondence between a simulation and site-specific information. Quantitative measures usually involve mathematical and graphical comparisons between measured and simulated aquifer heads, and the calculation of statistics regarding residuals (the difference between measured and simulated aquifer heads). Quantitative measures can also include comparison of simulated and measured components of the water budget, notably surface water flows, groundwater abstractions and evapotranspiration estimates.

Qualitative assessment of calibration is commonly undertaken by comparing patterns of groundwater flow (based on contour plans of aquifer heads or drawdowns), and considering the justification for adopting model aquifer properties in relation to measured ranges of values and associated non-uniqueness issues. Qualitative assessment is undertaken with due consideration for the adopted conceptual model.

This theme is covered by 13 guidelines. For example, guideline 3.2(g):

"It is highly preferable that a model is calibrated to a range of distinct hydrological conditions (e.g. prolonged or short term dry or wet periods, and ranges of induced stresses), and that calibration is achieved with hydraulic conductivity and other parameters that are consistent with measured values, as this helps address the non-uniqueness problem of model calibration."

Guidelines 3.3(b) and 3.3(c):

"The selected quantitative performance measures should be discussed and agreed between the client, project manager, modeller, and model reviewer, and may be subject to further negotiation at certain stages of the work in the light of data quality, etc."
"Plots of measured and modelled heads, residuals and/or error statistics should also be presented to indicate the spatial distribution of errors (e.g. scattergrams or contour plots of modelled heads with measured spot heights, or other error plots)."

The guide warns against being overly prescriptive in measuring calibration performance. The motivation behind applying prescriptive measures is to ensure that a contractor develops a valid, robust, rigorous model, based on an appropriate conceptual model and proper calibration procedures. However, any prescriptive measure is only enforceable if the data provided by the client is ample and appropriate for the task, and this is never likely to be the case. For example, there are always data deficiencies in time and space, particularly relating to groundwater and surface water level and flow data, and water usage metering. The data quality varies with time, often due to "rationalisation" of monitoring networks, resulting in incomplete databases, poor quality control, inadequate database management, obvious transcription errors, etc. Other problems relate to determining the extent of a prescriptive measure. For example, should a spatial measure apply to the whole area, and for which snapshots in time? For temporal measures, should it apply for the whole simulation period, and for which groundwater hydrographs?

It may be that an enforced prescriptive measure could lead to an erroneous calibration. This could happen if a modeller adjusts aquifer properties to ensure a better match of simulated heads with field observations, when in fact the field data might be wrong. If data quality is suspect or incomplete, a qualitative performance measure might be more reliable. It is rarely possible to say unequivocally that a model "is well calibrated", or "is not well calibrated". A model will in reality have a variable calibration performance, perhaps "good" in places, perhaps "poor" in places.

3.4 Prediction

Guideline 4(a):

"The initial set of prediction scenarios to be addressed following model calibration and verification should be limited in range, and outlined in the project brief in terms of:
- *the number of prediction simulations required and the types of prediction runs required (e.g. pumping rate ranges and timing, climatic variations, etc.);*
- *the prediction run timeframe and hydrological data set to be used (e.g. a repeat of the historical record, or the development of a synthetic data set for prediction);*
- *the type of sensitivity and/or uncertainty assessment."*

3.5 Uncertainty

Guidelines are offered for assessing the uncertainty in aquifer parameters, system stresses, and sustainable yield for resource management.

Guideline 5.4(c):

"For long periods of prediction (say, more than 10 years), a steady state prediction should be performed for at least three situations representing expected, dry and wet conditions; each situation should have an agreed probability of exceedance indicated by cumulative probability distributions for each stress. Alternatively, transient prediction approaches would also be acceptable, especially if it is important to also predict the time taken to achieve a new equilibrium ("steady state")."

Guideline 5.5(a):

"For low complexity models, a stochastic (e.g. Monte Carlo) analysis may be performed in order to assess the uncertainty in model outcomes due to uncertain aquifer property values."

3.6 Reporting and Archiving

Guideline 6.1(a):

"Reports should be submitted at specified stages throughout a modelling study to enable review of the technical and contractual progress achieved, and decisions to be taken on whether and how to progress the study. A minimum recommended reporting schedule comprises reports at the completion of the stages of Conceptualisation, Calibration and Prediction."

Guideline 6.2:

"Model archive documentation should be maintained, consistent with the procedures of the organisation undertaking the work. Commonly, an archive would comprise a combination of modelling journals, documents on pre- and post-processing data analysis, and modelling data and software program files. The objective is to document the modelling effort sufficiently such that the model could be re-generated for review and/or further refinement at some time in the future."

3. 7 Reviews

The integration of peer review at several critical stages through the project is another important method of improving modelling practice. The Australian guide proposes that reviews need to range from simple model appraisal using a checklist for simple models, through to more comprehensive peer reviews and complete model audits for more challenging complex models. The guide includes comprehensive checklists.

Guideline 7.2:

"To encourage consistency of approach between reviewers and between models, for models of medium to high complexity, a peer review should be conducted using a checklist of questions on (1) the report, (2) data analysis, (3) conceptualisation, (4) model design, (5) calibration, (6) verification, (7) prediction, (8) sensitivity analysis, and (9) uncertainty analysis. The review could be undertaken by an experienced modeller, different from the person who developed the model."

4. CONCLUSION

Best practice guidelines, specifically developed for application within the Murray-Darling Basin, are likely to be adopted for groundwater flow modelling Australia-wide. The guidelines address the processes of model design, calibration, prediction, uncertainty management, reporting and review. There has been a particular emphasis on producing best practice guidelines that provide support to modellers, but are still meaningful and useful to the community. A national workshop process was used to develop consensus, and a "plain English" summary guide is being developed for use by the community.

It is hoped that this guide will raise the minimum standard of practice in groundwater flow modelling without limiting the creativity required for good modelling practice. The guidelines also should not limit the ability of modellers to use simple or advanced techniques, appropriate for the study purpose. All aspects of the guide would not necessarily be applicable to every study, as models will differ in their levels of complexity. It should also be acknowledged that standardisation of modelling methods will not preclude the need for some subjective (and preferably experienced) judgment during the development of a model.

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