Identifying Uncertainty in Water Allocation Modelling

[1]Etchells, T. and [1]H Malano

[1]Department of Civil and Environmental Engineering, The University of Melbourne
E-Mail: teri@unimelb.edu.au

Keywords: *Water allocation; Reliability; Uncertainty; Model structure; Regulated systems.*

EXTENDED ABSTRACT

Water allocation models, sometimes referred to as water availability models, are critical tools for effective water resources management. Effective water allocation models allow policy-makers and managers to gain insight into the potential consequences of system changes, be they regulatory changes, infrastructure changes, climatic or other physical changes. Water allocation models are also used to set the expectations of water-entitlement holders regarding their 'security of supply'. These expectations play a significant role in determining the level of investment associated with irrigation and water use. Uncertainty around the security of supply has been shown to have significant negative impacts in reducing investment and undermining incentives for development. Therefore, it is vital that model output is robust.

Despite the importance of water allocation models, they are relatively under-researched and, probably, under-scrutinised. Water allocation models are extremely complex in form and function. In particular, they need to incorporate three domains: resources assessment (reflecting the hydrologic variability and storage behaviour), the allocation framework (reflecting the regulatory framework through entitlements, allocation processes and rules), and the demand module (reflecting the behaviour of water users) (Fig 1). These domains are constrained by the physical realities of any given system and must result in some distribution and routing of available resources in space and time.

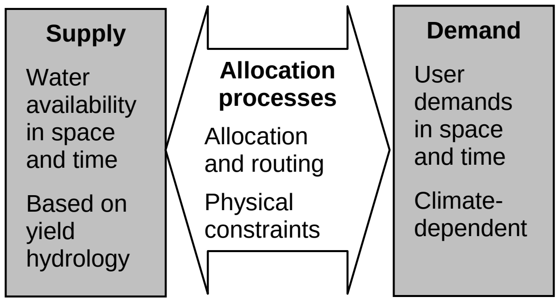

Figure 1. Components in water allocation models

Historically, existing water allocation models have been applied with success in the context of policy formulation. However, the current generation of models is not well positioned to deal with future demands. This is primarily since they have been built on relatively inflexible assumptions and processes reflecting historical system and user behaviour. Traditionally, these models produced deterministic outputs without explicit recognition of the uncertainty of the model structure, parameters, processes or inputs. Whilst the application of deterministic outputs may be appropriate for some analyses, consideration of uncertainty is necessary to improve the robustness of decision-making.

Much research has been undertaken dealing with uncertainty in modelling natural systems but there has been little attention given to water allocation models. This paper seeks to address this gap by identifying sources of uncertainty found in water allocation models and the particular modelling challenges presented this context. Findings are presented in the context of two established water allocation models used in Australia. These models primarily focus on rural, regulated surface-water supply systems.

1. INTRODUCTION

Water allocation models refer to models which estimate the quantity (and sometimes quality) of water resources available for allocation to users at a particular point in space and time. The model then allocates the available resource to various users who hold some entitlement. These entitlements could be for irrigation, urban, hydropower, environmental or other purposes.

Water allocation models are critical tools for effective water resources management. Effective water allocation models allow policy-makers and managers to gain insight into the potential consequences of system changes, be they regulatory changes, infrastructure changes, climatic or other physical changes. Water allocation models have been widely used in the formation of Australian water policy (Close; Department of Sustainability and Environment 2004; Lewis 2001; Murray Darling Basin Commission 1995).

In particular, water allocation models provide two main services:

- Insight into the likely consequences of policy changes, changes to physical infrastructure or changes to natural processes, such as climate or runoff processes (e.g. from bushfire). This is important because it helps ensure that sensible decisions are made in line with community expectations of efficiency, equity and sustainability.
- Help set expectations of water users with respect to reliability or 'security of supply'. This characteristic refers to the role of water allocation models in forming irrigator and investor expectations about the reliability of their entitlements. This can have a large impact on economic activity and help to foster investment in water use and water-dependent enterprises.

To meet these requirements, these models usually need to have a relatively large spatial scale covering multiple catchments. The spatial scale tends to be defined by a mix of institutional boundaries and physical boundaries. However, the level of spatial discretisation can vary in scale (e.g. farm, district). Additionally, the temporal scale can vary from daily to monthly, although it needs to be sub-annual since in order to capture seasonal effects.

Much research has been undertaken dealing with uncertainty in modelling natural systems but there has been little attention given to water allocation models. Water allocation models historically have been developed for specific jurisdictions in accordance with their institutions, geography and processes. As a result, the majority of literature on water allocation models has tended to focus on reporting the development and use of individual models rather than more general analysis of desirable characteristics of this class of models or assessing their robustness.

2. WATER ALLOCATION MODELLING

Water allocation modelling is different from traditional hydrologic modelling since user demands must be considered within the model as well as catchment processes. Intrinsically, these models must reflect human behaviour as well as physical processes. Furthermore, a key difficulty in conceptualising appropriate water allocation model structures is foreseeing potential policy change angles. Since a major role of these models is to test policy, an ideal structure will contain parameters and algorithms to enable many possible scenarios to be assessed.

Historically, existing water allocation models have been applied with success in the context of policy formulation (James et al. 1993). However, the current generation of models is not well positioned to deal with future demands. This is primarily since they have been built on relatively inflexible assumptions and processes reflecting historical system and user behaviour. Traditionally, these models produced deterministic outputs without explicit recognition of the uncertainty of the model structure, parameters, processes or inputs. Whilst the application of deterministic outputs may be appropriate for some analyses, consideration of uncertainty is necessary to improve the robustness of decision-making.

Water allocation models can be viewed as consisting of (at least) three domains: the supply module for resources assessment (reflecting the hydrologic variability and storage behaviour), the allocation framework (reflecting the regulatory framework through entitlements, allocation processes and rules), and the demand module (reflecting the behaviour of water users) (Figure 1). These domains are constrained by the physical realities of any given system and must result in some distribution and routing of available resources in space and time.

In general, water allocation models operate using water balance formulation combined with some sort of optimisation process to govern the routing of water in space and time. Typically, the optimisation is based on minimising criteria such as losses or restrictions.

As in any model, many decisions need to be made in model structure and formulations. In the case of water allocation modelling there are varying degrees of maturity in approaching the domains: supply, demand and allocation domains.

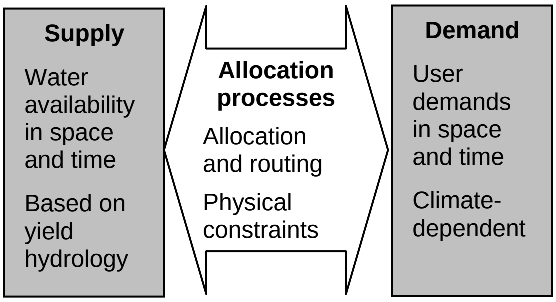

Figure 1. Key domains in water allocation modelling

2.1. Supply Domain

The supply domain is primarily focused on resource assessment. Typically, external rainfall-runoff and availability models are used to determine the inputs to the supply domain. However, these inflows need then to be routed to storages and appropriate inventories determined across space and time.

There is a large body of knowledge available to assist with supply modelling arising from hydrology. However, a useful summary is given by Grayson and Bloschl (2001) who outline three basic features helpful in summarising potential approaches for modelling in catchment hydrology:

(i) the nature of the basic algorithms (empirical, conceptual or process-based);

(ii) whether a stochastic or deterministic approach is taken to input or parameter specification;

(iii) whether the spatial representation is lumped or distributed.

As well as understanding the resources available, losses need to be reflected including both seepage and net evaporation; streams may interact with groundwater via recharge or discharge and drainage water from farms can return to stream. Many physical constraints exist in terms of system hydraulic capacity as well as the physical infrastructure available.

2.2. Demand Domain

The demand domain is an area of conceptual uncertainty within water allocation modelling. User demands are extremely complex and vary significantly according to the type of use, climatic considerations, individual user characteristics such as their risk propensity and, perhaps most difficult of all, water trading considerations (Figure 2).

Water trade modelling is perhaps the most uncertain component of water allocation modelling since little data exists to validate and populate potential models. Water trading itself involves a number of parameter and forcing variables such as commodity prices, the comparative price of water, the risk profile of users, the flexibility of trading policies and of course, the allocation itself. In fact, the interdependency of the volume of water trade (particularly temporary trade) and water allocation is a significant complicating factor in the model structure. This usually means a sub-optimisation module is required to model water trading within the overall allocation model (unless a time series or empirical approach is taken which is difficult given the sparse data sets often available in practice).

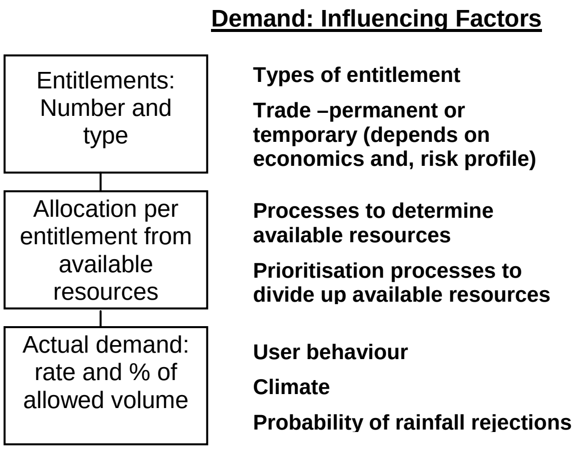

Figure 2. Components of demand module

Demand modelling depends heavily on climatic influences since there is clearly going to be an inverse relationship between demand and climate for consumptive uses. Additionally, isolated rainfall events can result in rejected water orders, particularly where no charges are incurred for rain rejections.

A key issue in selecting an appropriate demand modelling approach is a lack of demand data which occurs under relatively consistent conditions. In reality, available demand data is subject to continually changing conditions: changing water policies, commodity prices, water prices, trading rules, physical infrastructure and farm investment. These factors make it difficult to determine the key drivers of demand, particularly for water trade. Even the most conceptually simple task of identifying all entitlements in a rigorous way can be difficult since entitlements have been created in a variety of ways and are not usually registered in a central place. This situation is exacerbated when assessing demands associated with sources such as groundwater or local runoff (e.g. for farm dams).

In response to these issues a number of approaches have been applied to modelling demand. Some of these include empirical or time series approaches, quasi-economic approaches, models based on individual behaviour, models based on crop water requirements under particular climatic conditions (which ignore water trading) and a blend of the above. However, the lack of baseline data presents significant challenges in calibrating any of the above demand approaches.

2.3. Allocation Domain

A critical element in the model is the water allocation process: the mechanism by which available water is allocated to individual demands in space and time. Rules specific to individual jurisdictions apply regarding the priority for allocation of available water, and for delivery of that water. Water allocation processes at a system scale are enormously complicated both spatially and temporally.

Obviously, a water balance model across a catchment needs to represent a large degree of spatial and temporal variability for rainfall and runoff inputs as well as the infrastructure used to collect and distribute water. There are many rules and constraints to represent in the model such as rules governing the releases from storages depending on required reserves, releases for the environment and user demands. Specifically, key components in the allocation domain serve to:

- Describe all types of entitlements and associated conditions;
- Determine resource available for allocation that year (supply domain);
- Incorporate implications of allocation into estimates of water trading behaviour (demand domain)
- Determine demands associated with each type of entitlement (demand domain);
- Allocate available supplies to demands by entitlement type;
- Estimate likely temporal pattern of demands throughout year (demand domain);
- Route allocations throughout network within appropriate constraints by optimizing according to some objective function (e.g. by minimising losses within the system or maximising economic output);
- Determine resulting restrictions.

Overall, the main priority in the allocation module is to provide transparency around each of the above roles and to validate approaches where possible.

3. UNCERTAINTY IN WATER ALLOCATION MODELLING

In order for water allocation models to be valid, they need to accurately represent the significant features of real systems. However, developing a valid water allocation model is very difficult in practice. In particular, structural uncertainties in water allocation modelling can be very large and the changing nature of water policy makes it difficult to obtain comparative data. These issues make validation almost impossible and can undermine the integrity of model output.

Uncertainty has two significant negative impacts (on two different parties): it hampers policy decision-making (since decisions are difficult to determine and difficult to defend) and it reduces the ability of interested parties to form expectations about the future reliability of entitlements. This in turn reduces the ability of investors (in irrigation or environmental management) to plan and therefore increases their level of uncertainty. Increased uncertainty has been shown to reduce investment (Carey and Zilberman 2002; Dixit and Pindyck 1994) and therefore lowers productivity of water use (in terms of $/MegaLitre) relative to what it could be.

Historically, there has been little concern about the level of uncertainty in water allocation modelling. This has probably been due to the relatively low transparency in terms of water allocation policy, the relatively low value of water, limits on requirements for users to actively manage their water allocations and the relatively high ‘costs’ of understanding and addressing these issues. However, as Australian water resource management becomes ever more sophisticated, there needs to be a corresponding increase in the quality of management tools.

Haimes (1998) presents a simple framework for summarising sources of uncertainty based on two broad categories: variability, referring to the inherent fluctuation or differences in the quantity of concern; and knowledge uncertainty, referring to uncertainty due to limitations in the understanding of modelled processes. These two categories are then subdivided into several sub-categories (Figure 3) and help to describe the sources of uncertainty typically occurring in water allocation models.

Given the potential for uncertainty in water allocation modelling, the role of validation becomes critical. However, as has been widely acknowledged (Beven 1989; Grayson and Bloschl 2001; Post and Votta 2005) there is a relative immaturity in the application of processes to validate complex simulation models.

Robust validation is a difficult challenge for simulation models such as water allocation models. Post and Votta (2005) argue convincingly that current modelling is immature in terms of predictive performance and that improved software project management protocols can dramatically improve the quality of models. They note that even the most simple and proven techniques for managing code development are being employed in the computational sciences. They note that “the most common approach is the painful rediscovery of lessons already learned by others.”

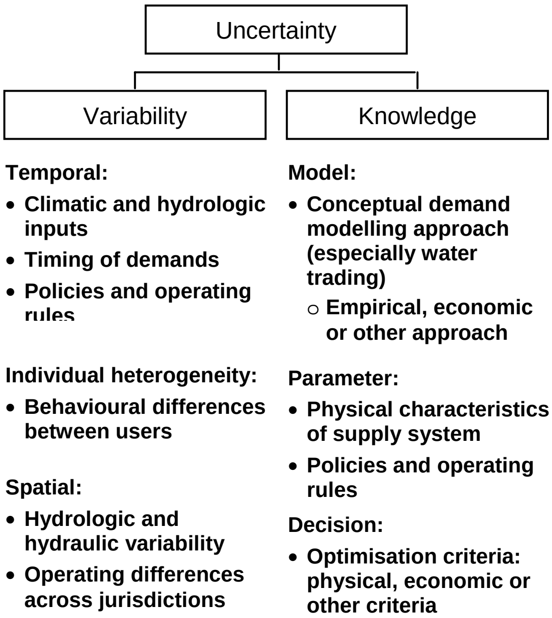

Figure 3. Examples of knowledge uncertainty in water allocation modelling

The output of existing models is used for a wide range of purposes and sometimes this output is used as the basis for further modelling e.g. modelling of the secondary economic effects, environmental flow and social effects resulting from water allocation policies. Given the current uncertainties and the lack of model validation, such analyses should be viewed with extreme caution since uncertainties are potentially large and are almost certainly unknown (Letcher et al. 2002).

4. CURRENT PRACTICE

There are three water allocation models widely used in Australia: Resource Allocation Model (REALM), Murray Simulation Model (MSM) and Integrated Quantity and Quality Model (IQQM). Whilst all the models are actively used for similar purposes, there are significant differences in their conceptual approach. Furthermore, there is little transparency around the uncertainty of outputs and of the potential ramifications of this uncertainty.

A diverse range of models have been developed internationally. For example, generalised simulation models have been developed for use in Texas (Wurbs 2005) and on the Syrdaya River Basin upstream of the Aral Sea (McKinney and Cai 1997). A comprehensive simulation model, named Calvin, is used in California (Jenkins et al. 2004). This model has a larger scope than the other models, optimizing according to economic and engineering criteria across surface water and groundwater resources.

4.1. Goulburn Simulation Model

Two calibrated models are summarised in this section: the Goulburn Simulation Model (GSM) (Department of Sustainability and Environment 2002; Victoria University of Technology and Department of Natural Resources and Environment 2001) which is a calibrated version of REALM (Hansen et al. 1992), and covers the Greater Goulburn Irrigation Area, and the MSM which covers the River Murray system throughout Victoria and New South Wales. Both models focus primarily on regulated surface water systems in the Murray-Darling Basin in Australia and were developed in the 1970’s – 1980’s. An overview of each water allocation model is given below describing the model’s defining characteristics in terms of parameters, forcing functions (exogenous time series), processes (time series, one time step) and states (time series, cumulative time steps).

Both models simulate water allocation in space and time, but use very different conceptual approaches. GSM operates on a monthly time-step at an irrigation district level. The system detail is available within GSM including detail on infrastructure, operating rules and allocation processes. This system detail has been summarised in Figure 4 as six major parameter types: infrastructure, including storages, the river and channel network, weirs and demand centres (either urban or irrigation demand nodes); operating rules, such as storage reserve policies, minimum release requirements, release rules; resource allocation curves governing the allocation that can be announced when a particular volume of water is available; limit curves governing the maximum cumulative rate of deliveries to various parts of the network; prioritisations governing the order applied to different parts of the network when restrictions occur; and capacity constraints associated with any storages, rivers or other infrastructure. Limited testing of the parameters in GSM have been undertaken showing that many parameters have little or no effect on outputs (Schreider et al. 2003).

GSM allocates water based on demands determined from a separate external model called PRIDE (Program for Regional Irrigation Demand Estimation). Studies such as Schreider et al (2003) have demonstrated that PRIDE also has significant issues of robustness.. Allocation processes within GSM rely on resource allocation curves that dictate the allocation that can be announced when a particular volume of water is available. These curves (one for each valley) were developed in the early 1990s, when GSM was initially developed, and implicitly assume a certain maximum utilisation for each allocation. These curves were based on past experience in those valleys. Since then, more entitlements are being used (as sleeping entitlements are traded) and a different quantity of entitlements or demand may exist in the valley. Therefore, these curves may not produce accurate allocations under current conditions, nor will they accurately determine allocations under different trading scenarios. Statistical methods will be used to understand the potential impacts of utilisation changes.

Parameter	Forcing	Processes	States
Infrastructure Operating rules Resource allocation curves Limit curves Prioritisation Capacity constraints (storages, rivers, outlets)	Inflows Monthly demands (from external crop requirement estimation model (PRIDE))	Available water River flows (from routing) Losses (evaporation, seepage, high flows) Reservoir operation Monthly deliveries Restrictions	District allocations* Annual deliveries to districts* Storage levels*

Figure 4. Overview of GSM structure

GSM uses inflows and monthly demand as its two main forcing functions, which are coupled with the parameters to drive six major processes: calculation of available water, network flows (determined using a network routing algorithm based on minimising costs entered as part of the infrastructure parameters), losses from evaporation, seepage and high flows, spills from storages exceeding capacity, monthly deliveries to demand centres and restrictions incurred at those demand centres (the difference between demand and deliveries). Finally, following on from these processes, three main states are monitored: district (or valley) allocations, annual deliveries (corresponding to utilisation) and storage levels.

The results of GSM rely on particular operating rules and assumptions regarding the level of development, which influence the volume of demand. The version of GSM used in this analysis is that used for determining the level of the Murray-Darling Cap for the Goulburn-Murray region. This means the level of development and rules are consistent with the situation in the 1993/94 season.

4.2. Murray Simulation Model

MSM is designed to address similar objectives to GSM: to model the demands, storage behaviour, system operation and flows in the basin (Close 2003). Like the GSM, MSM operates using a monthly time step and provides delivery information. However, unlike GSM, MSM does not separate districts, only diversions from the river. Additionally, MSM does not input demands as a forcing function, rather uses regression equations based on historical data (Figure 5). In particular, the regression equations are based on parameters including rainfall, temperature, declared allocations, last month's rainfall, last month's temperature and trend over time.

MSM relies on five types of parameters: infrastructure (e.g. storages and channels), operating rules, state allocation policies governing the calculation of allocations from available water, reserve policy (which dictates the volume required to be carried over in storage depending on system conditions such as the level of storages and target reliability levels) and capacity constraints of storages, rivers and other infrastructure. These parameters are used with four forcing functions (tributary inflows, rainfall, temperature and peak usage) to calculate the time series of monthly orders based on the regression equations. Two other processes are modelled including river flows (based on releases) and losses. Additionally, the model monitors five states including total irrigation demands (defined as diversions from rivers at key offtakes), water accounts for each state and valley, total diversions from river, allocations and storage levels.

Parameter	Forcing	Processes	States
Infrastructure Operating rules State allocation policy Reserve policy Capacity constraints (storages, rivers, outlets)	Tributary inflows Rainfall Temperature Peak usage (relationship of peak usage to declared allocation based on past usage)	Monthly orders from each storage (based on regression equation) River flows (from routing) Losses (evap., seepage, high flows) Available water Spills	Irrigation demands Water accounts Diversions from river* Allocations (state and valley)* Storage levels*

Figure 5. Overview of MSM structure

Given the dependence on historical data in determining future usage, MSM suffers from similar shortcomings to GSM in potentially underestimating future usage. Close (1989) notes that there is no guarantee that the historical relationship between declared percentage allocation and water use will not be exceeded, especially if more irrigators take advantage of temporary trading. The version of MSM used for this analysis is the equivalent to that used for the GSM: the Cap version with levels of development as at 1993/94.

Overall, these two models vary significantly in terms of their conceptual approach and model structure. Both have been extensively used for water policy development but need improvement to cope with current water policy questions.

5. CONCLUSION

The next generation of water allocation models should aim for improved robustness and incorporate considerations of uncertainty.

Overall there are four main challenges to address in water allocation modelling: increase the transparency and scrutiny of water allocation models; improve our understanding of conceptual approaches; improve validation processes undertaken in model development and finally; to reduce and represent model uncertainty wherever it exists. An improved approach to these issues is required for the next generation of water allocation models and should influence our interpretation of model results.

6. REFERENCES

Beven, K. (1989). "Changing ideas in hydrology - the case of physically-based models." *Journal of Hydrology*, 105, 105-172.

Carey, J. M., and Zilberman, D. (2002). "A model of investment under uncertainty: Modern irrigation technology and emerging markets in water." *American Journal of Agricultural Economics*, 84(1), 171-183.

Close, A. "Water sharing within the Murray-Darling Basin." Canberra.

Close, A. (1989). "River Murray water resource planning." *Proceedings of the national workshop on planning and management of water resources systems: Risk and reliability*, Adelaide.

Close, A. (2003). "Murray Simulation Model." Murray-Darling Basin Commission, Canberra.

Department of Sustainability and Environment. (2002). "Goulburn Simulation Model." Department of Sustainability and Environment, Melbourne.

Department of Sustainability and Environment. (2004). "Victorian Government White Paper: Securing our water future together." Melbourne.

Dixit, A. K., and Pindyck, R. S. (1994). *Investment under uncertainty*, Princeton University Press, Princeton, N.J.

Grayson, R., and Bloschl, G. (2001). *Spatial patterns in catchment hydrology : observations and modelling*, Cambridge University Press, Cambridge.

Haimes, Y. Y. (1998). *Risk modeling, assessment, and management*, Wiley, New York.

Hansen, W. R., Turner, G. K., and Adams, G. A. (1992). "Review of security of supply for irrigation systems." *Conference on engineering in Aagriculture: quality soils, quality food, quality environment*, Albury, 1-6.

James, B., Erlanger, P. D., and Hansen, W. R. (1993). "Modelling a complex irrigation restriction policy using a general simulation package." *Hydrology and Water Resources Symposium*, Newcastle, 221-226.

Jenkins, M., Lund, J. R., Howitt, R., Draper, A., Msangi, S. M., Tanaka, S. K., Ritzema, R. S., and Marques, G. F. (2004). "Optimization of California's water supply system: results and insights." *Journal of Water Resources Planning and Management*, July/August, 271-280.

Letcher, R. A., Jakeman, A. J., Calfas, M., Linforth, S., Baginska, B., and Lawrence, I. (2002). "A comparison of catchment water quality models and direct estimation techniques." *Environmental Modelling and Software*, 17, 77-85.

Lewis, D. (2001). *The value of water : a guide to water trading in Victoria*, Dept. of Natural Resources and Environment, East Melbourne, Vic.

McKinney, D. C., and Cai, X. (1997). "Draft working paper: Multiobjective water resource allocation model for Toktugul Reservoir." Austin, TX.

Murray Darling Basin Commission. (1995). "An audit of water use in the Murray-Darling Basin, Murray-Darling Basin Commission." Canberra.

Post, D. E., and Votta, L. G. (2005). "Computational science demands a new paradigm." *Physics Today*, January, 35-41.

Schreider, S. Y., James, B., Seker, M. P., and Weinmann, P. E. (2003) "Sensitivity and error propagation analysis for the Goulburn Simulation Model built by REALM." *Modsim 2003*, Townsville, QLD.

Victoria University of Technology, and Department of Natural Resources and Environment. (2001). "Realm version W1.4h." Melbourne.

Wurbs, R. A. (2005). "Modeling river/reservoir system management, water allocation, and supply reliability." *Journal of Hydrology*, 300, 100-113.