Sensitivity and Error Propagation Analysis for the Goulburn Simulation Model built by REALM

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Abstract: REALM is widely used in Australia as a water allocation management tool. In particular, this model is used in Victoria for water allocation planning in the Goulburn, Broken, Campaspe and Loddon River basins in North-east Victoria where water use is predominately related to irrigation. REALM represents the Goulburn-Broken catchment as a set of storage, demand and streamflow input nodes. These nodes are connected by a network of carriers characterised by their capacities and delivery priorities (represented as carrier penalties). The model is calibrated using a trial-and-error procedure, which optimises the model parameters to best represent the water supply infrastructure and the harvesting and allocation of water by the water authorities. Then, the Linear Programming (LP) based algorithm calculates the optimal distribution of water each time step of the simulation with the objective of minimising the sum of flow times carrier penalty over the system. The sensitivity analysis (SA) of REALM was implemented in relation to its most important input factors and output functions.

Keywords: *REALM; Water allocation; Goulburn Simulation Model; Sensitivity analysis*

1. INTRODUCTION

1.1. What is REALM?

REALM (REsource ALlocation Model) is used to model water supply systems in many regions of Australia (Diment, 1991; Perera at al., 2003). Some of the more complex examples of REALM applications are those for the Murray River system (Perera and Seker, 2000), the Melbourne metropolitan area (Perera and Codner, 1996) and the Goulburn water supply system (Perera and James, 1999), which is considered in the present paper.

REALM is a computer package which allows users to model distribution of water resources within the defined system of reservoirs, carriers and supply nodes. REALM uses a fast network linear programming algorithm for optimisation of water delivery (allocation) to different demand nodes.

Schematically, the major components of REALM are input processing, simulation and output processing (Perera and James, 1999). The first stage is related to the preparation of the streamflow, demand and system files. These variables are considered as external inputs and could be modelled independently. Simulation involves:

- definition of run time parameters
- getting information from set up
- simulation *per se,* which involves satisfying all demands, minimising spill, meeting reservoir targets and satisfying in-stream requirements.

The output step generates a set of output files with time series of different system characteristics, including carrier flows, reservoir levels, restricted demands *etc*. REALM can operate on a daily, weekly or monthly basis. Water demand in REALM is modelled externally using the PRIDE model (Erlanger et al., 1992).

1.2. The Goulburn Simulation Model (GSM)

The Goulburn Simulation Model built by REALM covers the catchments of the Broken, Goulburn, Campaspe and Loddon rivers, called the Goulburn System for the purposes of this paper. This region is a very important contributor to Australia's rural industry. Agricultural production in the Goulburn-Broken area alone is estimated at $1.35 Billion per annum, a significant portion of the total agricultural production in the state (Feehan, 2002). The use of groundwater resources in the Goulburn System is negligible compared to that of surface water resources and is not considered in the GSM.

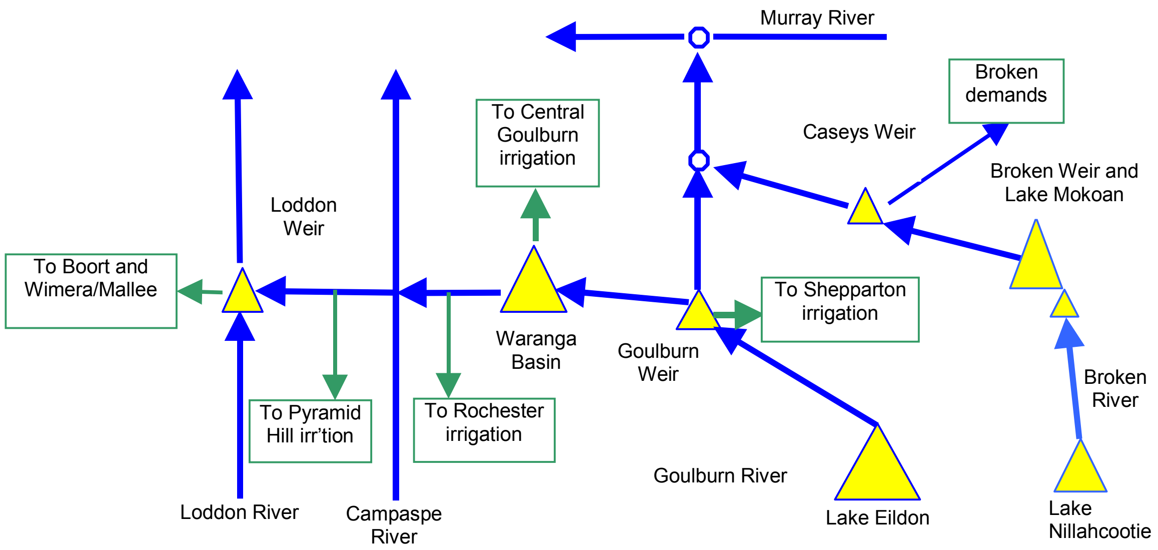

Figure 1. Simplified structure of the GSM (modified from Perera and Seker, 2000)

The GSM is used by the Victorian Government and water authorities in northern Victoria for determining Bulk Water Entitlements and for short and long term resource planning in the Goulburn, Broken, Campaspe and Loddon River catchments. The upper tributaries of these four catchments, upstream of the major reservoirs where irrigation use is very small, are not modelled within the GSM. The GSM runs on a monthly time step. Figure 1 shows a simplified schematic diagram of the GSM.

The sensitivity analysis (SA) of GSM was conducted in order to gain a better understanding of how uncertainty in key input factors is translated into variation of the most important GSM outputs. This analysis was implemented on a preliminary version of the Cap[1] model which was calibrated to the 1993/94 level of development. The analysis was restricted to the Goulburn-Broken catchment because it is one of the focus catchments of the CRC for Catchment Hydrology. The western border of the Goulburn–Broken sub-system is defined in the present work by the outflow from the Waranga Basin (Figure 1).

2. CALIBRATION OF GSM

The GSM represents the Goulburn System as a set of nodes of different types: storages, demands and streamflow inputs. These nodes are connected by a network of carriers characterised by their capacities and delivery penalties. Lake Eildon and Waranga Basin are the two major reservoirs in the Goulburn catchment, whose storage contents basically define the allocation level for the water users within the system. The GSM was calibrated using a trial-and-error procedure, which optimises the model parameters related to the water supply infrastructure (carrier capacities and losses, penalty functions, storage capacities). Then, the Linear Programming (LP) based algorithm calculates the optimal allocation strategy, in the sense of minimising the sum of flow times carrier penalties over the whole network. Other parameters relating to the LP algorithm, such as convergence criteria, which control how many times the LP is called, are also very important in the REALM calibration, and their influence on the model outputs was also examined. The process of model calibration is detailed in Perera and James (2003).

3. METHODOLOGY

The methodology of the SA selected for the present work is based on a simple input variation technique. The selected input parameters were varied within upper and lower limits of their plausible values, by assuming a uniform distribution over the interval and dividing it into 50 constant increments for n (n=51) replicates. Then the responses of the GSM outputs were analysed for the selected nodes in the Goulburn-Broken catchment.

There are about 90 nodes and 90 carriers representing the Goulburn-Broken part of the Goulburn System Model, and many more "accounting" carriers and nodes to represent the operating rules. With this very large number of parameters affecting the output functions, it would be an enormous task to examine the model

[1] The Cap is an upper limit on allowable diversions in the Murray-Darling Basin (MDB) and was introduced in 1997 by the MDB Ministerial Council.

sensitivity for all parameters. Therefore, only the input parameters, output functions and the GSM nodes thought to be most important were selected, employing the experience gained during the GSM calibration. Some subjectiveness in this approach is admitted, but it is postulated here as the most productive way of multi-parametric system analysis.

REALM is usually run using a graphical user interface to modify parameter values. As many hundreds of parameter adjustments had to be made in this analysis, a modified version of the REALM program was coded, allowing it to run in 'batch' mode for varying many parameters simultaneously.

4. SELECTED INPUT FACTORS AND OUTPUT FUNCTIONS

A list of the nine input parameters used in this analysis and their ranges is presented in Table 1.

The five most important GSM output characteristics selected for analysing the model's sensitivity to the selected parameters are:

- *Goulburn River outflow:* monthly modelled flow from the Goulburn River to the Murray River excluding Goulburn supplement releases for the area irrigated from the Murray, i.e. it is the environmental flow plus spills.
- *Broken River outflow:* monthly modelled flow from the Broken River to the Goulburn River, including environmental flows and spills.
- *Goulburn seasonal allocation*: the Goulburn allocation level at end of month as percent of basic water entitlement or water right. These values range from 0 to 200%. The key annual allocation statistic is the February allocation, which is the value calculated at the end of January.
- *Goulburn River Cap diversion:* represents the total modelled diversions from the Goulburn River, which is the Goulburn component of the Goulburn/Broken/Loddon Cap. The June value is the annual value for the financial year.
- *Broken River Cap diversion*: represents the total modelled diversions from the Broken River, which is the Broken component of the Goulburn/Broken/Loddon Cap. The June value is the value for the financial year.

5. RESULTS OF SENSITIVITY ANALYSIS

5.1. Output statistics

The SA of the GSM was implemented for the five output functions listed above The extremes of these functions, especially the minima, are the most important characteristics because they indicate the security of the system. As the Goulburn system is relatively reliable (compared with say the Wimmera-Mallee area in north-west Victoria) the average allocations calculated for 110 years are always above 100% of entitlement. The most interesting information for the water authorities in the region is to understand how the minimum allocation levels, occurring in very dry years, would change under different input factor fluctuations. Basic statistics (mean, maximum and minimum values, standard deviation and median) were calculated for all of these values over all replicates.

Table 1. List of key GSM inputs and parameters used in the sensitivity analysis

Parameter (calibrated value)	Meaning of parameter	Node/carrier type	Acceptable range
Goulburn River transmission loss (0.06)	Transmission loss as proportion of flow	variable capacity carrier	0.04 to 0.08; (-33% to +33%)
Goulburn Weir forced spill (function of flow)	Forces spills to simulate recorded diversion efficiency	variable capacity carrier	-50 to +50%
Storage convergence criterion (0.1%)	Defines tolerance for LP solution	linear programming parameter	0.1 to 5.1%
Carrier convergence criterion (5%)	Defines tolerance for LP solution	linear programming parameter	1% to 51%
Absolute convergence criterion (100 ML/month)	Defines tolerance for LP solution	linear programming parameter	10 to 1010 ML
Boort entitlement	Entitlement limit curve.	demand node	-50 to +50%
Broken River transmission loss (function of flow)	Transmission loss as proportion of flow	variable capacity carrier	-50 to +50%
Broken River operational loss (function of flow)	Forces spills to simulate recorded operational efficiency	variable capacity carrier	-50 to +50%
Waranga Basin evaporation loss coefficient (0.85)	Converts pan evaporation to lake evaporation.	reservoir node	0.5 to 1.0

The relative range (ratio of range to minimum) is used in this work as major characteristic of output variations. All input parameters, except the LP convergence factors, were artificially varied in a relative range of 100%.

5.2. Water allocation sensitivity

The only output function which consistently demonstrated a significant response to variations in the input parameters is the Goulburn seasonal allocation. Figure 2 presents how the October level of seasonal allocation responds to the variations of the Goulburn Weir forced spill factor. In October, the average level of water allocation fluctuates within the relative range of 8%, but the minimum level of allocation has a relative range of 66%.

Figure 2 demonstrates that a zone of stability exists for the forced spill factor values between 0.7 and 1.3, indicated by the water authority as the plausible range of variation for this parameter. The extension of this interval resulted in two jumps in the output variable. This was the only parameter that demonstrated stepwise jumps in an output variable.

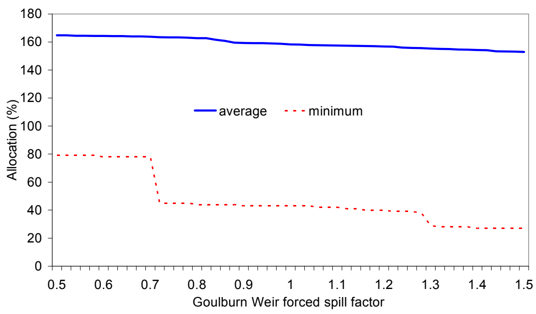

Figure 2. Sensitivity of the Goulburn allocation level in October to the spill limit

The response variation of the same output to the fluctuations of the Goulburn River loss factor is also quite high, with relative ranges of 38% and 28% for minimum allocations in February and August, respectively. However, the changes of these output functions are continuous. As would be expected, increasing the loss factor reduces the minimum allocation. Seasonal allocation in the Goulburn system responds in a similar way to the variation of storage convergence, although the trend is smaller and in the opposite direction. This implies that the security of supply could be slightly over-estimated if a large convergence criterion was used in REALM modelling.

5.3. Sensitivity of other outputs

The minimum outflow for the Broken River was shown to be very sensitive to the Broken River operational loss factor. The relative range reached a value of 293% for flow in October, with a range of 100%-200% in other months. The behaviour of this output function is illustrated in Figure 3.

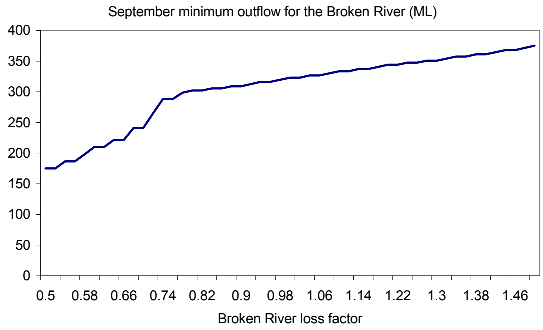

Figure 3. Sensitivity of the Broken River minimum outflow in October to the Broken River loss factor

Other output functions are less sensitive to the input factors. Table 2 summarises the maximum ranges of fluctuation of these functions as responses for all nine input factors. The important conclusion is that minimum values of output functions are the most sensitive to the variation of the input factors. The average values are the next sensitive, and the maxima are least sensitive.

5.4. Influence of inputs on output variations

Table 3 shows maximum sensitivity responses to all nine input factors, expressed as absolute values of their relative ranges,. This table provides the most sensitive and next sensitive outputs for each of the nine input factors. For only one output function, the minimum Broken River outflow, the level of variation is amplified. For all other outputs the variations are attenuated.

6. DISCUSSION AND CONCLUSIONS

The relative range of variation of almost all input factors, excluding the LP convergence parameters, is 100%. The relative ranges for outputs are consistently lower, except for the case of the Broken River outflow response to the variation of the operational loss in the river. Table 3 shows how this 'shock absorption' effect works where the maximally responsive output function reduced the input amplitude significantly.

Table 3 also demonstrates that the two most sensitive outputs to the input variations are the minimum Broken River outflow and minimum allocation level in the Goulburn System. The Cap diversions in the Goulburn and Broken Rivers are the next most sensitive parameters.

Table 2. Maximum relative ranges of output function fluctuations considered within the sensitivity analysis

Output function	Input factor providing max. variation (see Table 1)	For which month	Relative range (%) for min. values of this function	Relative range (%) for average values of this function	Relative range (%) for max. values of this function
Goulburn River Outflow	Broken River operational loss	October	30.1	0.2	0
Broken River Outflow	Broken River operational loss	October	293.3	2.7	0.2
Goulburn seasonal alloc.	Goulburn Weir forced spill	Nov.	68.4	7	0
Goulburn River Cap diversions	Goulburn Weir forced spill	Annual function	36.7	0.6	1.1
Broken River Cap diversions	Broken River operational loss	Annual function	27.8	1.3	0

Table 3. Maximum ranges of output function fluctuations (absolute values) for each input factor

	Input factor (see Table 1)	Most sensitive output function		Second most sensitive output function	
		Max. rel. range (%)	Output function and month	Max. rel. range (%)	Output function
1	Goulburn River transmission loss	37.8	Minimum Goulburn water allocation of Feb	25.1	Minimum Goulburn Cap diversion
2	Goulburn Weir forced spill	68.4	Minimum Goulburn water allocation of Nov, Dec[1]	38.8	Maximum Goulburn outflow of Mar
3	Storage convergence	18.6	Minimum Goulburn water allocation of Mar	10.8	Minimum Goulburn Cap diversion
4	Carrier convergence	28.2	Minimum Broken outflow of Nov	19.9	Minimum Broken outflow
5	Absolute convergence	0.04	Minimum Broken outflow in Feb	0.02	Average Broken Cap diversion
6	Boort entitlement	34.0	Min. Goulburn allocation of Sep, Oct, Nov, Dec[1]	18.0	Minimum Goulburn Cap diversion
7	Broken River transmission loss	12.9	Minimum Broken outflow of Aug	2.6	Maximum Goulburn outflow of Dec
8	Broken River operational loss	293.3	Minimum Broken outflow of October	42.1	Minimum Goulburn outflow of Nov
9	Waranga Basin evaporation loss	34.5	Minimum Goulburn water allocation of Oct, Mar[1]	21.9	Minimum Goulburn Cap diversion

[1] The same value of the output function applies for these months

Another important conclusion produced from this analysis is that the minimum values of output functions are generally much more sensitive than the average and maximum values of the same output functions.

The major lesson obtained from this exercise is that the GSM response to the input parameter variations is surprisingly low. It seems that for the majority of the output functions considered here, the GSM works like a shock absorber smoothing any large variations in model input parameters. The most likely explanation is that the Goulburn seasonal allocation process, which is central to the allocation and subsequent usage and outflows of water in the GSM, is a very stable and self adjusting mechanism. While this analysis shows that fluctuations in input parameters, such as transmission losses or diversion efficiencies (forced spills) do impact on the output variables, the water allocation processes within the GSM remain stable during these parameter fluctuations.

An interesting observation from this analysis is that the LP absolute convergence factor provides almost no effect on the outputs considered in this work. This is most likely due to the fact that the absolute convergence value (100 ML/month) used in the GSM has been set very small compared with typical flows in the system. If the percentage difference between two successive LP solutions is greater than the carrier convergence factor additional iterations are usually required, but if their difference is less than the absolute convergence factor no further iterations are required.

This parameter is effective in stopping unnecessary iterations that would produce large percentage differences and therefore would violate the carrier and storage convergence requirements (these are defined in percentage terms) but would provide little additional accuracy to the solution.

Analysis of results presented in Table 2 shows which input factors have the greatest effect on the GSM outputs. The important observation is that there are only two parameters that affect all five output functions. The Broken River operational loss generates the strongest response for the Goulburn and Broken River outflows and the Broken Cap diversion, whereas the Goulburn Weir forced spill factor is the most influential input for the Goulburn seasonal allocation and Goulburn Cap diversion.

Some practical recommendations that the water authority using the GSM for long-term assessment of the irrigation security may wish to consider are:

- When calibrating the model, special attention should be paid to the precision of the relationships defining Broken River operational losses and Goulburn Weir forced spills.
- The Broken River outflow should be given special attention during the calibration procedure. Some additional validation tests comparing modelled values with recorded flows might be beneficial.
- Some thought should be given to the singularities in the response of the minimum Goulburn allocation level to the variation of the Goulburn Weir forced spill, shown in Figure 2.

This work reports on the SA of the GSM in relation to the variation of single parameters only. Further work being undertaken in cooperation with scientists from Griffith University (Braddock and Schreider, 2003) is analysing the sensitivity of the GSM to the simultaneous variation of all nine inputs using the Morris algorithm.

7. ACKNOWLEDGMENTS

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8. REFERENCES

Braddock, R. and Schreider, S.Yu. Sensitivity analysis of the GSM REALM using the Morris technique (in preparation), 2003.

Diment, G.A. Wide use of the generalised headworks and resources model: REALM, *International Hydrology and Water Resource Symposium*, Perth, I.E. Aust., NCP No 91/22, 579-583, 1991.

Erlanger, P.D., Poulton, D. and Weinmann, P.E. Development and application of an irrigation demand model based on crop factors, Conference on Engineering in Agriculture, Albury, pp. 293-298, October 1992.

Feehan, P. The Goulburn Broken focus catchment, CRC for Catchment Hydrology, *Catchword*, 112, pp. 6-10, 2002.

Perera, B.J.C. and Codner, G.P. Reservoir targets for urban water supply systems, *Journal for Water Resources Planning and Management*, ASCE, 122(4), 270-279, 1996.

Perera, B.J.C. and James, B., REALM-REsource ALlocation model, Civil and Environmental Engineering Conference: New Frontiers and Challenges, 8-12 November, Bangkok, Thailand, V187-196, 1999.

Perera, B.J.C., James, B. and Kularathna, M.D.U. Computer software tool for sustainable water allocation and management – REALM, Proc. *International Congress on Modelling and Simulation MODSIM03,* Townsville, Australia, 14-17th July 2003 (this volume).

Perera, B.J.C. and Seker, M.P. Water quality modelling using REALM, 3rd International Hydrology and Water Resource Symposium, I.E. (Aust.), Perth, 20-23 November 2000, pp. 1075-1080