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OPTIMISIR: An optimisation tool to supplement REALM models or perform standalone optimisation of water resource systems

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Abstract: The current prolonged drought has caused significant impact on many Australian communities that rely on surface water. Water authorities and communities have responded with a range of demand management and supply augmentation measures that include water conservation, water restrictions, irrigation system modernisation and renewal, new connections and pipelines and alternative supplies such as rainwater, stormwater, recycled water and seawater desalination. For water resources systems that relied on relatively inexpensive surface water, the 'costs' involved in the construction and operation of some of the new supply schemes present new challenges in planning and operations. There is now an increasing need to optimise water systems considering economic, social and environmental factors.

Simulation modelling tools such as REALM have been widely used by many water authorities in Australia to assist with system planning and operations. REALM simulates the water allocation within a system in accordance with user-defined operating rules, but does not optimise the system operations over time. The operating rule inputs are often based on historical experience, or identified through trial-and-error processes. With the introduction of more expensive sources for which the optimum operating rules are yet to be identified, the limitations of such simulation tools have become increasingly evident. However, practical optimisation tools are not widely available or used, due to reasons that include the complexity of the approaches, expertise required, and the relatively inexpensive surface water sources that had been available.

This situation has prompted Melbourne Water to develop an optimisation tool OPTIMISIR (OPTIMISIng Resources) to serve two purposes: (1) link with and supplement the existing REALM model to improve its simulation outcomes and (2) perform standalone optimisation to assist in identifying the optimum annual operating outlook. When supplementing a monthly-time-step REALM model, OPTIMISIR identifies at each month the optimum operations for the next 12 months, and passes the optimum solution to REALM to simulate next month's operations in detail. This corresponds to a scenario in real operations of a monthly update of the optimum annual operating plan. When used standalone, OPTIMISIR outputs the optimum annual operating outlook through a user interface. In both modes of use, OPTIMISIR accommodates optional inputs from less detailed long-term optimisation approaches.

OPTIMISIR provides the choice of two optimisation methods: Linear Programming or Quadratic Programming, together with the flexibility for the user to specify system parameters and input scenarios and construct the objective function. When using Linear Programming, the model developed for the Melbourne Water Supply Headworks System representing 7 major harvesting reservoirs, the bulk water transfer system and 3 seasonal storage reservoirs close to Melbourne runs in less than 2 seconds in performing an optimisation for 12 months on a standard desktop computer used at Melbourne Water. The same model reformulated to run with Quadratic Programming takes about 6 seconds.

OPTIMISIR has been tested through a range of example scenarios and has shown the potential to be a suitable optimisation tool for the Melbourne Water Supply System. Further development and more detailed testing of the OPTIMISIR are currently being undertaken by Melbourne Water prior to its potential application as part of a suit of tools to optimise the water supply system. The planned improvements include the incorporation of an 'imperfect streamflow forecast' capability. This aims to address the current shortcoming of assuming perfect foresight of next 12-month's streamflows when the tool is linked to the REALM model. The paper presents the key features of OPTIMISIR and its application to the Melbourne Water Supply System under several hypothetical streamflow and demand scenarios.

Keywords: *Water Resource Optimisation, Linear Programming, Quadratic Programming, REALM*

1. INTRODUCTION

During the current prolonged drought that has continued for twelve years so far, Melbourne's water catchments have experienced the lowest recorded annual inflow in history. Water storage has fallen to a very low level despite many demand management measures that have been implemented. The low storage levels and the potential for future low streamflow scenarios has prompted the Victorian State Government to develop a series of water supply augmentations that include a water treatment plant to reconnect Tarago Reservoir to the system, Sugarloaf Interconnector connecting Melbourne to Goulburn River and a Seawater Desalination Plant. The high cost of operating these new water supplies has highlighted the need to optimise their usage. This contrasts with the historic goal in planning and operations of maximising the harvest from the relatively inexpensive surface water supply sources.

Despite many optimisation approaches reported in the literature, optimisation tools are not widely available or used in the water industry due to many reasons, the key ones being their complexity and the expertise required to structure and analyse optimisation problems. The simplifications needed to represent a complex system, lack of consideration about various goals in system operation and the difficulty in representing practical operations are some other factors that may have contributed to this situation. Past studies on optimisation commissioned by Melbourne Water are reported in Perera and Codner (1996), Perera et al (1999) and Perera et al (2005) and were aimed at optimising key operating rules used for planning purposes.

REALM (Perera, et al. 2005) is the key water resource modelling tool used by Melbourne Water to assist with system planning and operations. REALM is a generalised simulation modelling tool which is used to develop water allocation models for specific systems. REALM simulates the water allocation within a system in accordance with user-defined operating rules, but does not optimise the system operations over time. The operating rule inputs are often based on historical experience, or identified through trial-and-error processes. With the introduction of new augmentations with higher operating costs than current infrastructure, the optimum operating rules are yet to be identified. This highlights the need for the development of optimisation tools to supplement existing simulation tools.

Melbourne Water has developed the optimisation tool OPTIMISIR (OPTIMISIng Resources) to serve two purposes: (1) link with and supplement the existing REALM model to improve its simulation outcomes and (2) perform standalone optimisation to assist identifying the optimum annual operating outlook. OPTIMISIR provides the choice of two optimisation methods: (1) Linear Programming that has been cited in water resource literature over several decades (e.g. Loucks et al, 1981), and (2) Quadratic Programming. The novelty of OPTIMISIR is the linkages it provides to less detailed long term optimisation approaches as well as more detailed system simulation models, and its dual-purpose applicability in both planning and operations. This paper presents the key features of the OPTIMISIR and its application to the Melbourne Water system under hypothetically constructed streamflow and demand scenarios. In constructing the scenarios, historic scenarios and future forecasts have been avoided intentionally to avoid misinterpretation of the results as representative of the future operation of the Melbourne's water supply system.

2. MELBOURNE WATER SUPPLY SYSTEM

Melbourne Water provides wholesale water and sewerage services to three retail water companies serving the Melbourne metropolitan region; City West Water Ltd, South East Water Ltd, and Yarra Valley Water Ltd. Melbourne Water also provides supplies to Gippsland Water, Southern Rural Water and Western Water. Each retail water company has licence obligations to provide retail water and sewerage services within defined areas. An extensive transfer system links Melbourne's storage reservoirs with the city's three retail water companies and their customers. In 2008, the population served by the three retail water companies was approximately 3.8 million. The average volume of water supplied from the system for urban use during the last 5 years was 408 GL/year. Melbourne's current water supply system has a storage capacity of 1,773 GL, and is shown schematically in Figure 1. The current water harvesting and transfer system is largely gravity fed except for the Sugarloaf Reservoir's harvest which is pumped and subsequently fully treated, and the supply through Yan Yean Treatment Plant.

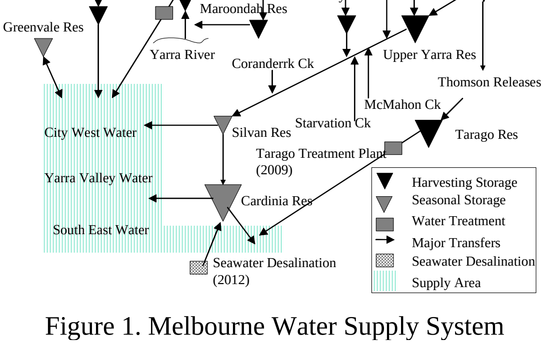

Figure 1. Melbourne Water Supply System

Figure 1 also shows the planned future supply sources that include a seawater desalination plant, Sugarloaf Interconnector connecting Melbourne and Goulburn River and Tarago water treatment plant for reconnecting Tarago Reservoir (38 GL in capacity) to the system. The planned new supply sources involve water treatment and pumping and will be potentially more expensive to operate than the predominantly gravity supply sources of the current system. These new supply sources are referred to as the 'higher cost sources' in the remainder of this paper.

Streamflow into Melbourne's water supply is impacted by relatively high climate variability. Historical records that commenced in 1913 contain drought events of 1914/15, 1938/39, 1967/68 and 1982/83 that were relatively short, and the current long drought that started in 1997. Despite the large storage capacity of the system, prolonged drought periods can cause significant drawdown of system storage levels over a number of years, resulting in water restrictions.

3. CURRENT MODELLING APPROACH

Melbourne Water uses the REALM headworks model (Perera et al, 2005) to simulate the behaviour of its water supply system. REALM is the standard tool used by water authorities in Victoria for water resource system simulation. Being a generalised tool for developing a simulation model for a specific water supply system, REALM allows the behaviour of the system (e.g. storage volumes and transfers) to be simulated for a range of operational and climatic conditions. The key application areas of Melbourne Water's REALM model include the augmentation planning, drought planning, water entitlement assessment, environmental flow assessment and the evaluation of alternative operating strategies.

Melbourne Water's REALM simulation model represents the harvesting and transfer system in much greater detail than Figure 1, and models the supplies to retail companies through 17 demand centres across Melbourne. Among the key aspects modelled are all harvesting sites, major reservoirs and transfers, influence of climate variability on monthly demands, demand restriction rules, environmental flows, harvesting by pumping from Yarra River into the off-stream Sugarloaf Reservoir, treatment plant outputs, and a range of operating rules. The model uses a network linear programming optimisation algorithm to spatially allocate water within each time step. However, as indicated in Section 1 a key limitation of REALM, being a simulation tool, is the absence of an optimisation over time. As an example, REALM simulates water 'harvesting' decisions each month without considering the consequences in the months ahead. As a result, the modelled harvest volumes from the higher cost sources might not be optimal over time. The absence of an optimisation approach also means that many REALM runs involving a trial-and-error approach are needed in identifying the 'best' augmentation plan or operating strategy for the system.

Currently, Melbourne Water's REALM simulations are carried out using stochastically generated or historical monthly streamflow and climatic data and future demand forecasts. Historical streamflow sequences are adjusted where required to model climate change impacts. They are subsequently 'recycled' within REALM to create a number of potential data replicates (McMahon and Mein, 1986). For long term planning, the system is simulated in monthly time steps for up to 50 years into the future.

4. MODELLING APPROACH WITH OPTIMISIR

4.1. Introduction

OPTIMISIR aims to serve two purposes in two different modes of use. In long-term water resources planning mode, it can link with and supplement REALM simulations by addressing one of REALM's key limitations which is the absence of an optimisation over time. In operation optimisation mode, it can serve as a standalone optimisation tool for assisting with shorter-term (currently annual) operation optimisation.

In both modes of use, OPTIMISIR identifies the operations that optimise the value of an objective function subject to a range of constraints. Examples for objective functions include minimisation of the total annual cost of system operation and minimisation of the total annual volume of system outflows. Examples for constraints include asset capacity limitations, environmental flow requirements and the budget available for operating expenditures.

4.2. Key Features of OPTIMISIR

The key features of OPTIMISIR are summarised as follows.

- OPTIMISIR is a computer program which can be linked to REALM models under long-term water resource planning mode or run standalone in shorter-term operation optimisation mode

- Provides the choice of two optimisation approaches: linear programming or quadratic programming
- Enables user to construct the objective function and constraints. Any linear objective function or some non-linear objective functions can be constructed using the set of variables used to define the system
- Seamlessly links with REALM using the capability of REALM to run an external routine during the simulation. Flexibility exists to link with other simulation tools that have similar capabilities.
- Incorporates long-term optimum operating guidelines through water value functions (Section 4.5)
- The OPTIMISIR's 'engine' is largely generic and is separated from user inputs that define the water resource system and the optimisation problem's objectives and constraints.
- Short run-time as demonstrated by the Melbourne water supply system model which takes less than 2 seconds with linear programming, and under 6 seconds with quadratic programming, in performing an optimisation for a 12 month period
- Combined use of simulation and optimisation approaches (in planning mode) addresses the limitations of each individual approach and creates a powerful modelling tool
- In operation optimisation mode, OPTIMISIR provides a Microsoft Excel based user interface which includes graphical and numerical interface components to assist in the identification of the optimum annual operating outlook.
- Currently set up to optimise the system operation for any 12 month period but provides the flexibility to incorporate longer periods

4.3. OPTIMISIR's Role in Planning (REALM Supplementation)

OPTIMISIR's role in planning is to address one of REALM's key limitations which is the absence of an optimisation over time. OPTIMISIR addresses this issue by linking with REALM to perform a supplementary optimisation in time and space. Figure 2 outlines the REALM simulation process supplemented by the OPTIMISIR. As shown in Figure 2, REALM takes a range of inputs including system operating rules to simulate the system operation in each individual time step of the model run. In a REALM simulation, the continuation from one month to the next is provided by the modelled end-of-the-month storage volume which becomes the starting storage volume for the next month. REALM simulation does not 'look ahead' to optimise the system operations over time.

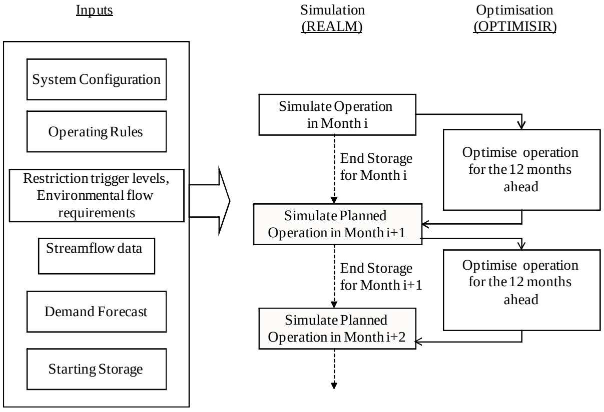

Figure 2. REALM Simulation Process Supplemented by OPTIMISIR

When OPTIMISR is linked, it runs within the REALM simulation process and 'looks ahead' to identify the optimum key operating decisions for the next 12 months before passing control to REALM to simulate next month's operation. This process of 12-month optimisation followed by 1-month simulation is repeated for each month of the simulation run. In other words, in each month of the simulation run, OPTIMISIR prepares an 'optimum annual operating outlook' which specifies the optimum operating decisions for the subsequent 12 months and then passes this information to REALM to simulate next month's operation in detail. In supplementing the REALM model, OPTIMISIR represents the role of a system operator who attempts to operate the system by preparing at each month an optimum operating outlook for the 12 months ahead based on the information available at the time.

The input data requirements of the OPTIMISIR are similar to REALM with the exception that OPTIMISIR does not require short-term operating rules as they are identified through the optimisation process. In terms of streamflow scenario to be used, OPTIMISIR provides two options (1) input data sequence or (2) imperfect forecast based on the input data sequence. The first option is currently implemented and the second is a planned addition. The first option is useful in identifying the optimum operations under particular historical scenarios. The second option, when used in supplementing REALM, is likely to produce modelling results that better represent the level of optimality that can be achieved with imperfect forecasts in real operations.

4.4. OPTIMISIR's Role in Operation Optimisation (Standalone Use)

OPTIMISIR provides an optional standalone user interface based on Microsoft Excel enabling its standalone use with no links to REALM. As shown in Figure 3, this mode enables optimising the system operation for a given 12-month streamflow scenario, system demands and start storage conditions.

Figure 4 displays the Microsoft Excel user interface which displays the optimal operating decisions and system behaviour graphically. Additional worksheets included in the user interface provide a range of information covering individual system components and system water balance.

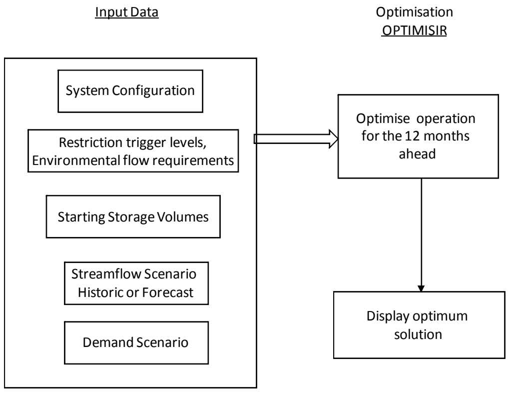

Figure 3. Standalone Use of OPTIMISIR

4.5. Use of Carryover Water Value Function (CWVF): Key Link to Long-Term Optimisation

OPTIMISR enables the optional incorporation of carryover water value functions (CWVF) to address the potential issue of short-term optimisation failing to consider long-term objectives. CWVF provides a key link between short-term and long-term optimisation which is a critical component for Melbourne Water Supply System given the potentially large carryover storage volume in the system.

The use of CWVF is explained below using an example optimisation problem formulation of minimising the operating cost of a water supply system such as Melbourne's which can have a potentially large carryover storage volume. If this system is optimised for one year under the objective function of minimising the operating cost alone, the obvious solution would be to turn off the most expensive water sources with the exception of those that are essential to meet the demands, and drawdown the storage. This solution is clearly unacceptable under very low storage conditions, and may be undesirable even under relatively high storage conditions. The cause of this undesirable solution is the incomplete objective function which ignores the value of carryover storage at the end of the optimisation period or the cost of restrictions. The CWVF addresses this issue. As shown in the hypothetical example shown in Figure 5, it indicates to the OPTIMISIR that if the carryover storage level is very low, the unit value of water ($/ML) is very high, and if the carryover storage level is very high, the value of water is very low. The form of the CWVF has an important influence in the short-term optimisation. The CWVF is best identified through long-term optimisation considering the trade off between financial expenditure and the potential 'cost' of longer term restrictions or water shortages. In regards to the long-term optimisation approaches in water resource optimisation, the potential of Stochastic Dynamic Programming has been demonstrated by many researchers including Kularathna (1992) and Hughes et al (2008). The latter details a methodology on how the water value functions can be identified in a transparent manner considering water pricing as an alternative to restrictions. Their methodology is equally applicable for estimating water value considering restrictions.

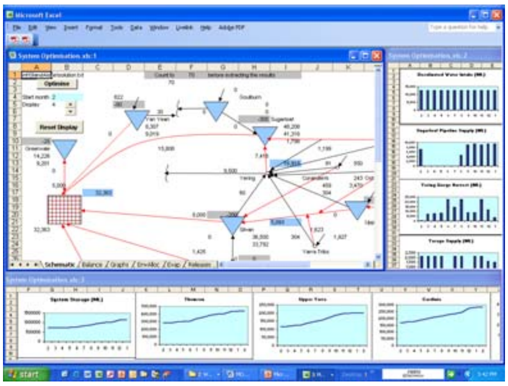

Figure 4. Graphical User Interface for Standalone Use of OPTIMISIR

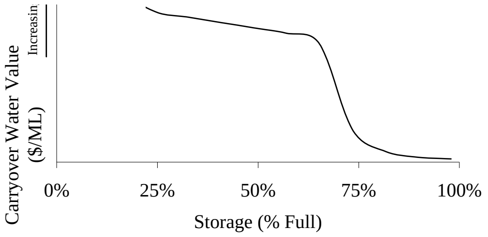

Figure 5. Example for Carryover Water Value Function

In the absence of long-term optimisation, an initial approximation of CWVF may be produced by assuming that the high water value would be close to the cost of the most expensive source and the low value is close to zero. The function may subsequently need to be refined iteratively considering the implications on long-term system behaviour.

5. EXAMPLE APPLICATIONS

An OPTIMISIR model of the Melbourne Water supply system was developed using more than 550 decision variables. This formulation opens up many operating decisions for the analysis, not just the decisions on higher cost water intakes. The model represents the system operation over any 12-month period and includes many constraints representing environmental flow requirements and asset capacity limitations.

The above model was used to demonstrate OPTIMISIR's potential to optimise Melbourne water supply system using hypothetical streamflow and demand scenarios. Due to the nature of the hypothetical scenarios and the use of preliminary model parameters including assumed carryover water value functions the modelling outcomes described in this paper are for illustration purposes only and should not be considered as indicative of the potential system behaviour. Description of the streamflow scenario used to identify these outcomes is intentionally omitted from this paper due to the same reason. Further development and more detailed testing of the OPTIMISIR are currently being undertaken by Melbourne Water prior to its potential application as part of a suit of tools to optimise the Melbourne water supply system.

5.1. REALM Supplementation

Two REALM model runs of the Melbourne Water Supply System were undertaken with and without being supplemented by OPTIMISIR, to simulate the operation of the system for 45 years in monthly time steps. Both model runs were started with a relatively high start storage volume of 1500GL representing an 83% full augmented water supply system.

In the REALM run without OPTIMISIR, the REALM model attempts to maximise the harvest in each monthly time step. This can lead to modelling of larger water intakes from higher cost sources, as the potential in subsequent months for high streamflows from lower cost sources is not explicitly considered.

The REALM run supplemented by OPTIMISIR addresses this issue, as OPTIMISIR prepares at each monthly time step of the simulation an optimum 'annual operating outlook' for the 12 months ahead. The key intake decisions of REALM are subsequently altered based on this outlook, causing a reduction in the modelled intake volumes from the higher cost sources. In this example, OPTIMISIR used the objective function of minimising the downstream releases. With this objective function, incorporation of the carryover water value function is unnecessary, as the value of water is implied by the objective function. OPTIMISIR was provided with the same dataset available to REALM. This resembles a hypothetical scenario in actual operations in which the system optimisation for the 12-months ahead is always performed using a perfect streamflow forecast. As a result, the results indicate the upper bound of the outcomes achievable in actual operations by implementing this type of an optimisation approach. The capability to consider an imperfect forecast is a planned future addition aimed at representing a more realistic operation scenario.

Table 1. Summary output of REALM runs with and without OPTIMISIR

Model Run	Average intake from higher cost sources (GL/year)	Average outflow from the system (GL/year)	End storage (% full)
REALM run without OPTIMISIR	246	305	90.2%
REALM run supplemented by OPTIMISIR	222	281	89.5%
Difference (%)	-10%	-8%	-0.7%

The results in Table 1 indicate that when the REALM model is supplemented by OPTIMISIR, the modelled average annual intake from higher cost sources has reduced by 10% and as a result the modelled average outflow from the system has reduced. However this has caused a reduction in the storage volume at the end of the 45-year model run. This minimal storage reduction is attributed to the approximations involved in the optimisation process and the direct use of OPTIMISIR's output to control the REALM simulation process. Improvements to this process are planned to enable REALM to use the optimum results 'more intelligently', by making use of more detailed information available to REALM.

5.2. Standalone Use

OPTIMISIR was used to identify optimum operations for a 12 month period for the Melbourne Water Supply System under artificial streamflow and demand conditions and two different objective functions. Where required, an assumed carryover water value function resembling Figure 5 was used. The optimum outcomes for 5 different model runs are summarised in Table 2 and discussed below. To make the comparison between different model runs easier, the same annual demand has been used in all 5 runs.

Table 2 shows the modelled total intake volumes from the higher cost sources. In Table 2, the least cost solution for Run 1 which started with a 40% full storage indicates a very high intake from the higher cost supply sources. Run 2 was undertaken without the carryover water value function, implying incorrectly to the model that water in storage has no value. The corresponding least cost solution reduces the intake from higher cost sources, except for small volumes that are essential to meet the demands under the modelled transfer capacities. Run 3 starts with a relatively high start storage volume and results in a small increase in storage. The solution in Run 3, in comparison to that of Run 1 shows the trade off between the cost of water intakes and the value of water in storage. The high start storage level in Run 3 and the resulting high end storage level (which is associated with low carryover water value) have caused large intakes from higher cost sources to be uneconomical in Run 3.

Table 2. Optimum solutions for a 12-month period under standalone mode

Run	Description	Start Storage (% full)	Intake from higher cost sources (GL)	End Storage (% full)
1	Minimise (operating cost - CWV*)	40%	363	65%
2	Minimise operating cost	40%	18	38%
3	Minimise (operating cost - CWV*)	85%	59	90%
4	Minimise downstream releases	40%	363	65%
5	Minimise downstream releases with annual operating budget constraint	40%	265	60%

*Carryover Water Value

Runs 4 and 5 were done with the objective function of minimising downstream release volumes. This objective function represents one of the key goals modelled by the REALM model, however the key difference between OPTIMISR and REALM is that REALM does not 'look ahead' to optimise the operation in time. Run 4 has identical outcomes to Run 1, highlighting that under very low starting storage conditions, the optimal operation involves maximising harvests from all sources. In Run 5, a budgetary constraint caused OPTIMISIR to limit the harvest from the higher cost sources.

6. CONCLUSIONS

The paper demonstrates the potential of OPTIMISIR to be a suitable tool for identifying optimum system operations for water resource planning and operation optimisation purposes. For the above two purposes, the same tool can be used in two different modes, either as an add-in to the REALM model or as a standalone tool. In the planning mode, OPTIMISIR seamlessly links with REALM and runs in the background at each time step of the REALM simulation, continuously providing REALM with the optimum operating outlook for the 12 months ahead. The use of the carryover water value function enables OPTIMISIR to incorporate longer term optimality considerations within a short-term optimisation approach. The preliminary applications presented in this paper indicate the potential of the tool in optimising the system operation under various scenarios. Further development and testing are currently being undertaken by Melbourne Water prior to its potential application as part of a suit of tools to optimise the Melbourne water supply system. Planned developments include an 'imperfect streamflow forecast capability' to address the current shortcoming of assuming perfect foresight of next 12-month's streamflows when the tool is linked to the REALM model.

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