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Improving the efficiency of delivering water in Australian river systems: modelling multiple paths

Gilmore, R.L.[1,2,3]**, Kuczera, G.**[2,3]**, Penton, D.**[1,2]**, and Podger, G.**[1,2]

[1] *Commonwealth Scientific and Research Organization (CSIRO), Australian Capital Territory,*
[2] *eWater Cooperative Research Centre, Australian Capital Territory*
[3] *University of Newcastle, New South Wales, Australia*
Email: rachel.gilmore@csiro.au

River managers and modellers use long term planning models to inform river operators and planners on how to best operate regulated river systems. Long term planning models simulate the regulated river system using either rules based approaches or linear optimisation techniques. This paper compares these two approaches and examines the potential for objective driven solutions to be used to generate better rules in the Lachlan River System in NSW, Australia.

Multiple supply path problems occur when water can be sourced from storages in parallel, storages in series or delivered by parallel distribution paths. Multiple supply path problems are typically complex and difficult to solve. Both rules based models and objective driven (optimisation) models are used to solve multiple supply path problems for long term planning in Australia's rural catchments. Rules bases models such as the Integrated Quantity and Quality Model (IQQM) and MSM-BigMod have been used to model rural catchments in Queensland (IQQM), NSW (IQQM) and the Murray River (MSM-BidMod). Optimisation models have been used extensively in Australia for urban water supply modelling and in Victoria for rural and urban systems (REALM, (Diment, 1991), and WATHNET). Specific system information on tradeoffs between the two modelling methods (e.g. efficiency, accuracy of complex processes, and runtime) could be obtained relatively easily by modellers if the software allows a choice of approaches or a combination of approaches.

Currently rules based long term planning models are typically run on a daily time step while the optimisation models are run on a monthly time step. It is considered important to be able to run models on either a monthly, daily or sub daily time step. There are run time implications for use of optimisation on daily to sub daily time steps. It may be preferable to model only part of the system with optimisation and the rest with a rules based model which is an option for the Lachlan example.

This paper focuses on a case study for supply through multiple paths on the Lachlan River System in NSW that is traditionally modelled using a rules based model (IQQM). Implementing an objective driven model decreased the volumes ordered from the multiple supply paths by 55% and reduced shortfalls by 7% of total demand relative to the rules based model. Using the NetLP solution to generate new distribution rules for orders in IQQM reduced the volumes ordered by 13% and reduced shortfalls by 5.4% of total demand relative to the original IQQM. This illustrates the benefit to river operators and planners of having NetLPs in software packages for long term planning models. Objective driven solutions can be used to generate more efficient rules where a rules based model is preferred, however there will still be tradeoffs in efficiency, modelling accuracy of complex processes, and runtime.

Keywords: *Multiple supply, Water resource, Rules, Heuristic, Optimization, Optimisation, Network Linear Program*

1. INTRODUCTION

Multiple supply paths problems occur when a regulated river system has users that can order water from multiple supplies of water or where there are multiple paths to a water supply. Allocating water efficiently in multiple supply path scenarios is a difficult problem for operators, modellers and software systems alike. New software modelling tools need to adequately address multiple supply path issues to satisfy the needs of river modellers. Multiple supply path problems are complex to solve. Two modelling approaches are traditionally implemented to solve multiple supply problems in eastern Australia, 1) rules based models (eg IQQM, MSM-BIGMOD) and objective driven models (REALM, WathNet). Both modelling approaches have their advantages. Rules based solutions typically have faster run times and can model complex processes and rules but do not search for the most efficient solution. Objective driven models can produce more efficient management solutions to multiple supply path problems, but can have large runtimes when there is a large number of nodes, small time steps, or long travel times (depending on the method travel times are applied). Many existing rural systems would have configurations of nodes and travel times that would exceed the acceptable limit for run time of existing optimisation algorithms. Accurately modelling complex processes can also fall into this category.

This paper investigates the implementation of optimisation algorithms for key parts rather than the whole of the river system, to minimise the effect on run times. The Lachlan river system (NSW, Australia) provides an example of this type of problem. This paper investigates the potential to implement optimised solutions to multiple supply path problems on the Lachlan river system. An approach is proposed where the optimised solution is only applied to the part of the river system that has multiple supply path problems. The rest of the river system is solved using a rules based solution to minimise the effect on run times. This study compares implementations of the rules based software IQQM (Simons, 1996, Hameed and Podger, 2001, Hameed and O'Neill, 2005) and the optimisation software WathNet (Kuczera, G.,1992) which is a generalised Network Linear Program (NetLP). A NetLP is a simplified form of linear program with faster runtimes than the general linear solvers. The objective function in WathNet minimises volumes ordered and shortfalls in deliveries to users.

The Lachlan river system has traditionally been modelled with IQQM a rules based simulation model that can model complex river basin rules and behaviour with small runtimes. The 111 year IQQM model of the Lachlan used for in the Murray Darling Basin sustainable yields audit (CSIRO, 2008) takes approximately 6 minutes to run. This runtime allows river management planners to simulate numerous scenarios in their day-to-day work. To demonstrate the difference in modelling part systems as optimisation, sub-models of the Lachlan in both IQQM and WathNet have been compared. The area modelled includes the multiple supply path area and orders from downstream of the multiple supply path area. Figure 1 has the multiple supply path area marked in bold. This has a 'bottleneck' configuration where all water supplied to the multiple supply path area and downstream must pass through the multiple supply area. The optimisation minimises orders at the top of the multiple supply area (point A) including the orders from downstream of the multiple supply area from the rules model at point B. Efficiencies in modelling the delivery of water as well as the sharing of demand shortfalls is central to operation of the Lachlan river system.

2. CATCHMENT DESCRIPTION

The Lachlan River flows in a westerly direction from its headwaters in the foothills of the Great Dividing Range and terminates in the Great Cumbungi Swamp near Oxley in southeastern Australia (Figure 1). It is an example of a multiple supply path problem embedded in an elongated rural supply valley. Wyangala Dam, located upstream of Cowra at the confluence of the Lachlan and Abercrombie rivers, is the major water storage within the region with a storage capacity of 1218 GL. Small instream storages include Carcoar Dam and numerous smaller weirs along the length of the Lachlan River (CSIRO, 2008). Lachlan river system within the Murray Darling basin in south eastern Australia showing surface water features and the multiple supply paths area adapted from CSIRO (2008). Figure 1 shows key features of the Lachlan river system, notably includes the environmentally significant wetlands at Booligal and the Great Cumbungi Swamp in the lower sections of the river (Figure 1). The area defined with the bold black line between points A and B approximates the area where multiple supply path modelling was carried out separate from the main system, and is referred to as the multiple supply paths or MS Area in the rest of this paper.

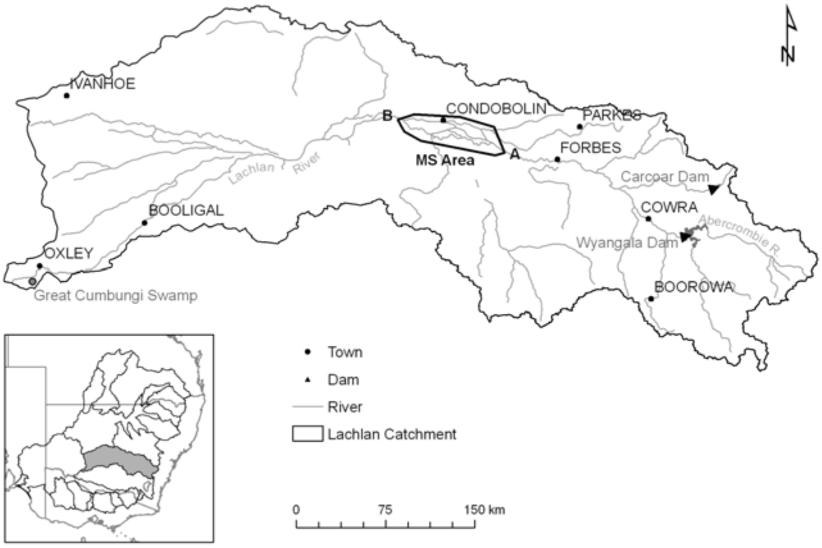


Figure 1. Key features of the Lachlan River System, NSW, Australia.

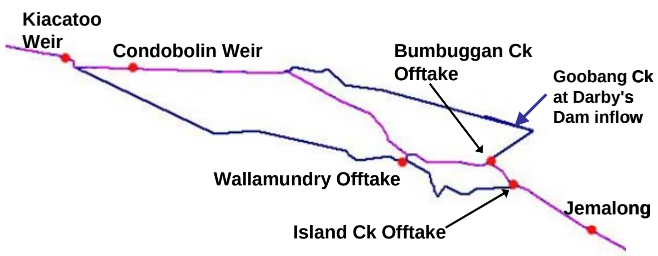
The Lachlan river system demands are either above the multiple supply path section, in the multiple supply path section or below the multiple supply path section; the proportions in each section are shown in Table 1. Sixty-six per cent of the total Lachlan demand/supply occurs within or flows through the area that requires optimising, since supply downstream is constrained by the multiple supply paths (57%).

Table 1. Average demand above and below the multiple supply paths for the Lachlan river system.

Group	Demand (ML/d)	% of Total Demand
Above multiple supply path section	408	34
Multiple supply path section	110	9
Below multiple supply path section	699	57

Figure 2 shows the multiple supply paths are made up of the mainstream Lachlan River downstream of Jemalong, the Island Creek offtake on the south side of the river, and the Wallamundry offtake coming off Island Creek further downstream. Both these creeks rejoin the Lachlan river downstream. On the north side of the Lachlan river Bumbuggan Creek offtake creates the forth supply path. Unregulated flows are fed into the system by Goobang Creek at Darby's Dam.

Figure 2. Multiple supply path detail on the Lachlan River System, NSW, Australia.



3. METHOD

Sub-models of the Lachlan have been developed for a rules based (IQQM) and an objective driven (WathNet) solution to the MS path area (Figure 1). These models have similar characteristics so that their outputs can be directly compared. The IQQM model of the Lachlan river system from the Murray Darling

Basin Sustainable Yields Project, (CSIRO, 2008) was used as the source of data (orders from the regulated irrigators and supplementary diversions within and downstream of the MS paths) and system configuration. A period of 01/06/1895 to 30/06/2006 was used to capture the river management planning horizon. The historic climate series and current development conditions (CSIRO, 2008) were also used. Both the IQQM and WathNet models begin with a storage at the top of the river network and the same supply constraints (i.e. Wyangala inflows and storage characteristics). Goobang Creek (412043) is added as unregulated inflow. The demands at the bottom of the system are the orders from all the irrigators downstream of the multiple supply paths combined at point B, Figure 1.

The configuration of the IQQM and WathNet models is similar (Figure 3) except IQQM uses only 1 link to represent regulated effluents whereas WathNet has 2 arcs one for the minimum and one for additional flow up to the maximum regulated capacity.

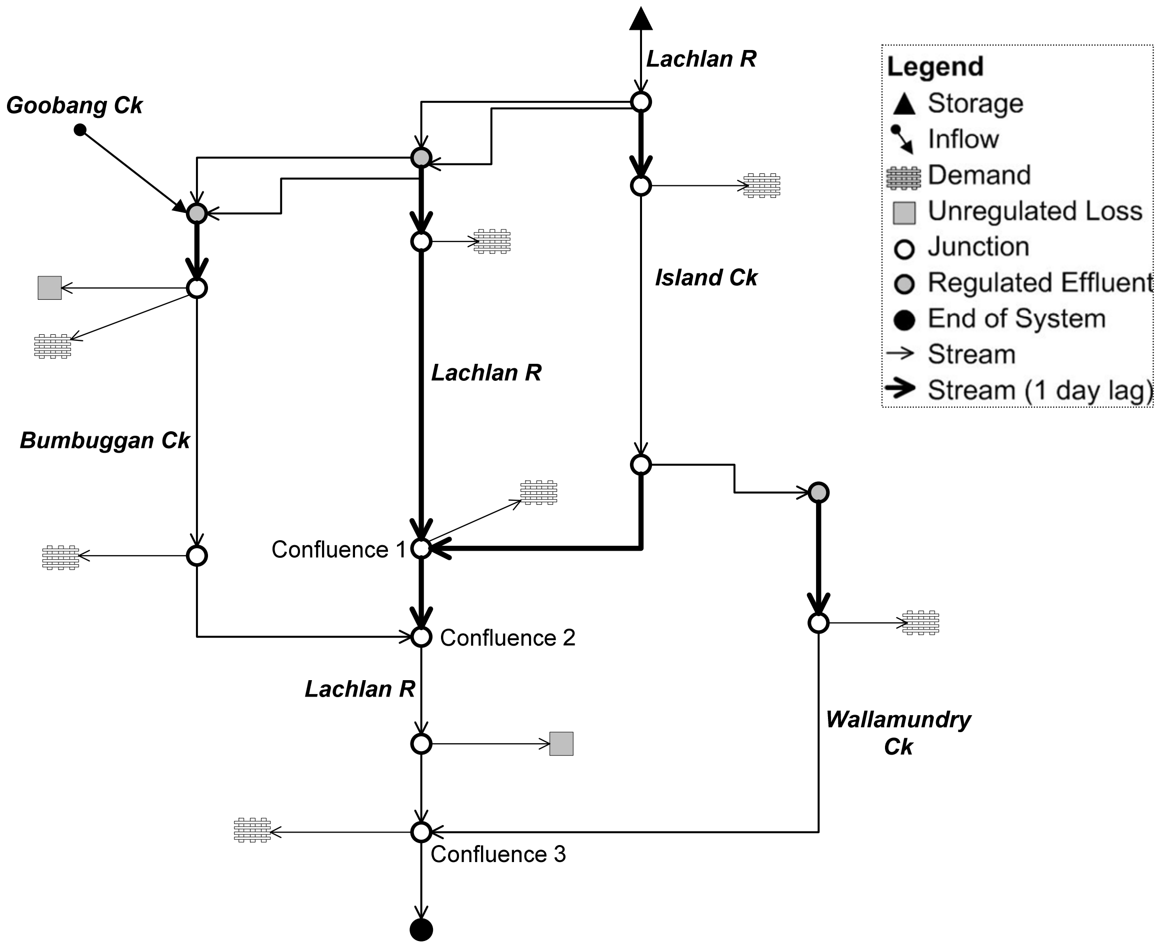


Figure 3 Schematic diagram of the multiple supply paths

3.1. IQQM System Configuration

The IQQM has the following:

- two piecewise linear relationships between upstream flow and unaccounted loss on Goobang Creek and the Lachlan river upstream of the Wallamundry Creek return,
- two regulated effluents (Island Creek and Bumbuggan Creek offtakes) which have a minimum amount to be diverted for any given upstream flow, and an additional amount that can be diverted down the effluents according to supply path for meeting downstream demands,
- a regulated effluent (Wallamundry Creek) with a fixed piecewise linear relationship that diverst flow down Wallamundry Creek according to upstream flow,

- flows are lagged, according to travel times, rather than using complex routing,
- travel times to the major storage (Wyangala Dam) begin as 0 days at the inflow to the multiple supply paths, and end at 3 days downstream of the Wallamundry return, and
- all demands have the same priority of supply.

3.2. WathNet System Configuration

WathNet is a generalised network linear program (NetLP) that uses an algorithm called RELAX-IV (Bertsekas, 1991) to solve the NetLP, (the same algorithm used in REALM (Perera and James, 2003)). The algortihm minimises the orders at the top of the multiple supply area (point A), whilst accounting for demands both within the MS area and downstream of point B.

An additional WathNet model was run to obtain an estimate of unconstrained orders. Being an optimisation model WathNet has no concept of orders since it sees demands and distributes water holistically in one step. The orders version of WathNet is the same as above but with an unlimited supply reservoir at the top. This determines how much water could be released to meet demand accounting for system losses had there not been any constraints on supply from the dam. WathNet orders will be used interchangeably with data from the original WathNet model since they represent the same scenario.

The WathNet system configuration has:

- minimum effluent flows were entered with a cost incentive so that the NetLP would always apply them. The maximum effluent constraintss were added as additional amounts with no cost so that flows above the minimum and up to the maximum amount were optional and could be apportioned by the NetLP,
- the regulated effluent Wallamundry Creek offtake and the unaccounted losses are implemented into WathNet with cost incentives so that the NetLP always implements them,
- travel times in days were added to arcs corresponding to the lags on the links in IQQM, and
- the number of shortfall arcs for each demand was 5, the base penalty was the same for each demand (none had priority over the other).

3.3. Revised IQQM

A revised version of the IQQM model was made by analysing the NetLP solution to generate new rules for distributing orders to upstream branches at the 3 confluences shown in Figure 3. All the original IQQM model confluences split orders by 50% up each branch. Branch 1 is the horizontal link and branch 2 is the vertical link into each of the confluences in Figure 3. The revised IQQM split orders at:

- confluence 1 by 59% up branch 1 for orders > 620ML/d, and 84% for orders ≤ 620 ML/d,
- confluence 2 by 74% up branch 1, and
- confluence 3 by 90% up branch 1.

The new distribution rules are from a preliminary analysis only to demonstrate whether this process is useful.

4. RESULTS

In general, the WathNet solver keeps more water in storage, supplies more demand, has increased unaccounted losses, and an overall decrease in waste compared to the IQQM, (waste is the sum of Unaccounted Loss and the Outflow Gauge). The Unaccounted Loss relationships are derived from the difference between gauged inflows and outflows, metered diversions, and estimated ungauged inflow for a reach during the calibration period. They can be made up of evaporation loss, surface-groundwater interactions, unmetered diversions, and estimation or reading errors.

Table 2. Summary comparison of the IQQM and WathNet models.

1895-2006	IQQM (ML/d)	WathNet (ML/d)	Difference (%)
Demand	809	809	0%
Shortfall	69	12	-7%*
Storage Change	-22	-1	-93%
Total Inflow	2185	2185	0%
Unaccounted Loss	130	242	86%
Outflow Gauge	1337	1147	14%
* Difference % of demand			

A summary comparison of results is given in Table 2 and Table 3. The first item to note is that WathNet orders less from the dam 824 ML/d than IQQM 1,822 ML/d to supply the same demand of 809 ML/d. The 1,822 ML/d IQQM order is not always available at the dam due to supply constraints so only 1,622 ML/d was released. Despite much larger releases by the IQQM, it had more shortfalls than WathNet (8.5% compared to 1.5% of demand). Table 3 shows the more efficient allocation of water by WathNet resulting in more water being stored in Wyangala. As a result it had less air space to store unregulated inflows and hence spilled more often. The overall release and spills from both models are approximately the same but the degree or regulation is much more in IQQM i.e. there are more releases and less spills.

Table 3 Summary comparison of results for Wyangala Storage

Wyangala Storage	IQQM (ML/d)	WathNet (ML/d)	Difference (%)
Orders at the Dam	1822	824	-55%
Releases	1622	819	-49%
Spills	413	1195	189%
Total	2034	2014	-1%

Overall, using WathNet has:

- decreased the volumes of accumulated orders from the multiple supply paths by 55%.
- reduced shortfalls by 7% of total demand.
- significantly increased spilling of Wyangala.

As IQQM is a rules based solution the efficiency of the system will rely on the efficiency of the rules that are implemented in it, and also the flexibility in implementing rules in the model. To demonstrate that the NetLP solution can be used to develop more efficient rules, the new rules for distributing orders to upstream branches described in section 3.3 was applied to the IQQM model. This resulted in a 13% reduction in orders (1,585ML/d) and a 5.4% reduction in shortfalls (25ML/d) as a percentage of total demand compared to the original IQQM model. While this is not as dramatic as the NetLP it represents a substantial improvement in model performance.

The runtime for WathNet (Relax-IV algorithm) is 3.5 times slower than IQQM.

5. DISCUSSION

The similar amount of total releases and spills between the IQQM and WathNet models is deceptive. IQQM releases large amounts of water to meet demand matching its ordering scheme, and therefore has more storage space to catch unregulated inflows. WathNet conserves water by supplying demands efficiently and increases the volume of water in storage over time. This reduces the air space available to catch unregulated inflows and so it spills more frequently. This represents an opportunity for redistributing water in the system, perhaps for environmental use. For example, a translucency demand downstream of the multiple supply paths cuts out when the storage falls below a certain volume/allocation (Podger and Hameed, 2000). In WathNet the downstream translucency orders are likely to be more and would result in more water released for environmental purposes.

Waste is the sum of Unaccounted Loss and the Outflow Gauge. To maximise efficiency the total waste is minimised. WathNet has slightly less waste than IQQM although this would be much less if there wasn't forced spilling (described above). WathNet has more Unaccounted Loss than IQQM since it chose to send more flow down the paths with Unaccounted Losses on them. WathNet does this because the overall waste can be minimised by adjusting the utilisation of the regulated effluents. WathNet also has more spills than IQQM and experiences higher losses at higher flows.

The rules based model (IQQM) has faster runtimes for the same network, however compared to simulation of the full Lachlan system in IQQM, the addition of 1 minute to 6 minutes may be acceptable given the improvement in the solution. The runtimes of the NetLP solvers is significantly impacted by the number of iterations to reach a solution and the number of nodes and arcs. Therefore, it will be necessary to explore more complex systems to understand the full impacts on run times using an optimised based solution.

River managers value the transparency of rules-based models. Many believe that rules-based models are more defensible because the choice of path is defined by the rules. This means for the Lachlan system that choosing a rules model will provide a less efficient solution than a NetLP. Use of part system optimisation may help address this by trading off some transparency to gain efficiency through the multiple supply paths and model the rest of the Lachlan system with rules. If an entire rules based model is required, the modeller could use optimisation simulations to inform the development of better rules.

CONCLUSIONS

There was a significant efficiency gain by using an optimisation model for the multiple supply paths in the Lachlan River system over the rules based model. The NetLP solution was used to develop new rules for distributing orders in IQQM resulting in improved model performance.

If the capability of part system optimisation was made available in water management software, the modelling efficiency of planning and operating systems could be improved from current practice. If only the capability for whole systems to be simulated by both solvers is introduced, rules based and optimisation simulations could be done on the same system and compared without extra work by the modeller in setting up the models. In part or whole system simulations the modeller would be better informed when trading off efficiency or modelling accuracy of complex processes for reduced runtime or other objectives.

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