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Incorporating Hydraulic Criteria into a Water Mass Balance Model for Optimal Operations

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Background and relevance

In 2009, during one of South Australia's most severe droughts, the decision was made to improve water security by building the Adelaide Desalination Plant (ADP). To maximize the benefit of using the ADP several upgrades to Adelaide's distribution network were implemented which enables water to be transferred from the ADP in the south to northern residential areas. Previously the separate areas of Adelaide were each supplied from catchments in the Adelaide Hills, augmented by pipelines from the River Murray, hence water generally travelled from east to west. Several decision support tools, discussed in Duncker et al. (2014), were developed to manage the increased flexibility and complexity of the operational environment and maximise opportunities relating to system interconnectivity. One of these tools is the Distribution Optimisation Tool (DOT), which determines optimal water sourcing and transfer options for the Adelaide metropolitan network.

DOT is a mass balance model and uses Linear Programming (LP) to optimise operational costs such as pumping and water treatment. Network Linear Programming (NetLP) is an alternative optimisation method used in WATHNET (Kuczera 1992), REALM (Perera & James 2003) and SOURCE (Delgado et al. 2011. Kuczera et al. (2009) identify some problems with NetLP; the primary one being that each timestep is optimised independently so future planned infrastructure outages (e.g. pump maintenance) cannot be ameliorated in earlier timesteps. The counter-criticism of LP is that it uses future unknown data as if it were known (e.g. inflows to storages). Ideally the random variability of data such as inflows and demands would be accounted for formally through the use of Stochastic Dynamic Programming (SDP). Unfortunately SDP is not practical from a computational perspective. Cervellera et al. (2006) found that for a model with 10 reservoirs and 30 discretizations of the uncertainty variables to solve a single time-step model takes nearly 3 hours of computing time. DOT has a similar number of reservoirs but optimizes over more than 100 time steps.

Therefore either LP or NetLP should be used. The key benefit of NetLP is its faster run-time. However, that benefit would be trivial for DOT as the LP-based optimisation takes less than 1 minute. Hence LP was selected as the optimisation method.

In order to use LP, some hydraulic constraints, which are by nature non-linear needed to be linearized. The following is a summary of what that entailed and how it was achieved in a computationally efficient manner.

Results and Discussion

Link-Flow Rules

There exists a hydraulic relationship in any pipeline between the capacity of the pipeline and demands taken off the pipeline; specifically, higher demands result in reduced transfer capacity. In order to include realistic constraints in DOT, several runs of a hydraulic model were used to determine the relationship between online demands and pipeline capacity; these were the link-flow rules. At the start of each optimization run the demands in each time-step are calculated and the corresponding link-flow rule is used to determine the capacity of each pipeline at each time-step. The demands considered range from low winter demand to peak summer demand, and they will only need to be recalculated if there is a physical change to the distribution system and the hydraulics change.

Cost-Volume Curves

Cost-volume curves are used for modelling pumping stations. They are used to determine the cost of pumping a certain volume of water within a certain timestep. A cost-volume curve is applied to a pumped pipeline (not a pump station), which includes a pump station and connecting pipelines between two nodes. Like the link-flow rules, hydraulic relationships are developed offline with a hydraulic model. For cost-volume curves, the data is the flow through the pipeline for a given online demand from the pipeline, each combination of pumps that can run in parallel, and the power consumed by the pump(s). Full details on how these curves are constructed are based on the method presented in Crawley and Dandy (1993), but a typical curve is shown in Figure 1. The final step is to convert this non-linear curve it into a series of straight line segments. The curve is then in a format that can be used in a linear program.

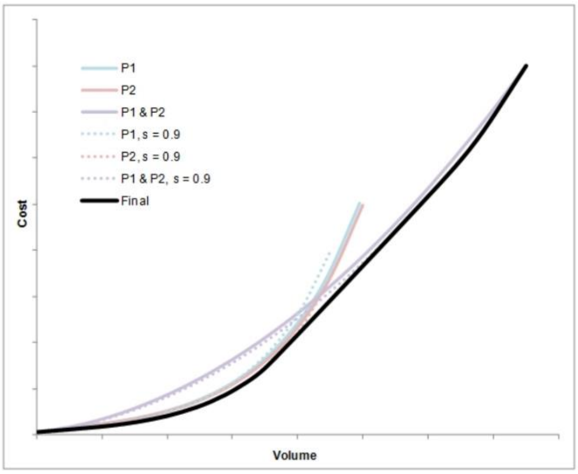

Figure 1. Example cost-volume curve.

Evaporation Curves

Evaporation curves provide the relationship between storage volume and evaporated volume for a given time-step (see Figure 2 for an example). They are constructed from depth-volume-area data for a storage and the evaporation depth (in mm) for a time-step. The resultant curve is convex (cf. concave cost-volume curves), therefore the equations required to approximate the curve linearly is more complex, in that it involves integer variables. To solve an LP with integer variables the Branch-and-Bound algorithm (Land & Doig 1960) is typically used, which has an exponential relationship between run-time and the number of integer variables, as demonstrated in Table 1. Table 1 shows that having more points per evaporation curve increases run-time to an impractical level. While more points per evaporation curve will provide a more accurate model the degree of added accuracy is quite small. The total evaporated volume difference between 2 and 3 point curves is 1171 ML (over a 2 year simulation period), and as a percentage of total demand is just 0.34%; a trivial difference.

Table 1. Results from long term DOT model with different numbers of points per evaporation curve.

Points per Evaporation Curve	Total Integer Variable	Run-time (s)	Total Evaporation Volume (ML)
2	0	1	30074
3	1456	19	31245
4	2912	6000+*	N/A

* Feasible solution could not be found within given time.

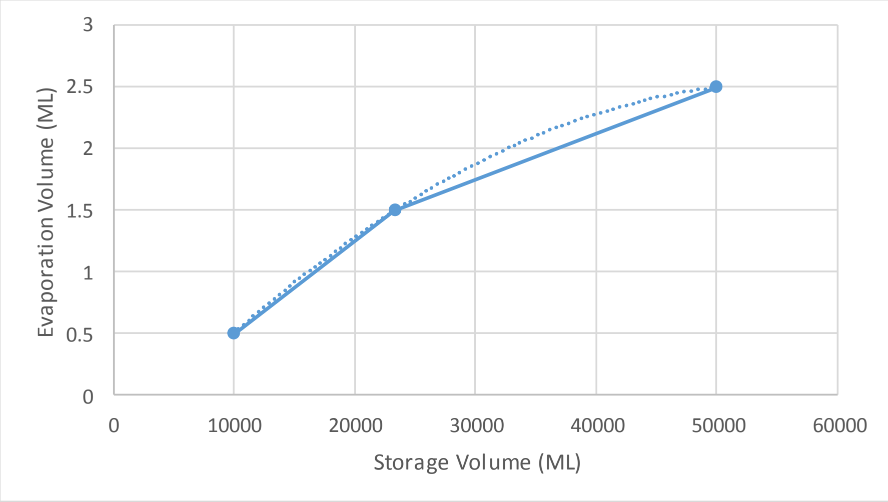

Figure 2. Example evaporation curve with three points in the linearized approximation.

Summary of Key Findings

This paper presents some key components of the optimization algorithm in DOT used by SA Water for optimizing its bulk water supply operations. A brief justification is provided for using LP rather than NetLP, which has been used in similar software recently. The main focus of the paper presents several methods for incorporating hydraulic criteria into the model, which is a key aspect allowing DOT to be used in a water utility operations centre. 1. Link-Flows rules leverage offline use of a hydraulic model to determine realistic capacity constraints within pipelines dynamically (i.e. they're updated for each optimization run). 2. Cost-Volume curves also utilise a hydraulic model and combine that data with live electricity tariff forecasts to produce sufficiently accurate linear relationships between cost and volume pumped. 3. Evaporation curves are used to calculate the volume of water lost due to evaporation. Numerical analyses show that trading off very small amounts of model accuracy significantly reduces run-times from completely impractical to the order of 1 second. 4. The computational speed of DOT reinforces the findings of Crawley and Dandy (1993) and Broad et al. (2012) by validating the use of LP for optimizing bulk water supply systems rather than the reportedly faster but more simplified approach, NetLP.

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