A Water Balance Model for the Simulation of Complex Headworks Operations

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EXTENDED ABSTRACT

Balancing water supply with demand is under stress in Australia and many other countries where fresh water resources are scarce. It is essential to develop a better water resource planning and management strategy to reduce the risk of supply shortage. A computationally efficient basis for water balance simulation amongst the nodes of a multiple reservoir system is important to assess alternate operational plans and policies. This study is part of an Australian Research Council and Sydney Catchment Authority funded project that aims to develop a generic basis for probabilistic forecasting of reservoir inflows into the Sydney Catchment Authority water supply system. One of the outcomes desired from this study is a modeling platform that enables the probabilistic forecasts to be coupled to a water supply reservoir simulation model. This paper presents the basis of a water balance model for the simulation and evaluation of water supply headworks planning and operations that is being developed. The model uses system and network node water mass conservation as a sole constraint and hence allows users to specify operating rules at individual nodes to enable water distribution across the entire network system. Optimization of water allocation to meet downstream demand is achieved by estimating net water availability called virtual storage at each non-reservoir node. The model adopts a variable computational time step, ranging from hourly to yearly, enabling the real time simulation of various hydrological events, such as flooding and long term drought, to be carried out for risk management studies. For the purpose of medium term prediction of reservoir storage against demand, the new model provides an interface with which a multi-site probabilistic stream flow forecasting model can be directly coupled. An important aim in developing the model is to ensure minimum computer run time and simplicity of interpretation, given the uncertainty associated with the likely operational policies the model would suggest when coupled to the probabilistic forecasting system. Consequently, simplistic assumptions are made to distribute the water downstream of any node with the aim of executing the simulation without resorting to optimization at each time step. As an alternative, cost based optimization algorithms are intended to be included into the model to perform the same operation, at a later stage.

The modeling system has been developed with Intel Visual Fortran using Microsoft Visual Studio .Net as a platform, which allows visualization and animation of real time reservoir storage and river flow to be possible at a later stage of the model development.

In this paper, we describe the development of the new model and show an example of model application to the Sydney Catchment Authority water supply network system for the simulation of multiple-reservoir system operations using a period of ninety years of historical stream flow records. Based on the analysis of the preliminary results, the proposed model has been found capable of producing reasonable results in simulating multiple-reservoir system operations.

1. INTRODUCTION

Balancing water supply with demand is increasingly becoming a critical issue in Australia and other countries where fresh water resources are scarce. In recent years, Australia has experienced one of its longest drought periods causing reservoir storage to drop below levels that have forced operators to impose mandatory water restrictions. This is coupled with the threat of global climatic change, with the expectation that summers will get hotter and hotter in the future, with implications for higher water demand. At the same time, population growth inevitably increases the consumption of water. These factors combine to contribute to the supply shortage crisis with the expectation that this crisis will be further deepened in the future.

As groundwater is saline in most areas, water supply to major cities in Australia is mostly dependent on systems of several reservoir storages. The increased demand requires either constructing new reservoirs or managing more carefully and judiciously existing water resources. Developing a good water supply planning and management strategy requires the management authority to have some idea of the relationship between water availability and demand for the forthcoming years. A possibility of achieving this objective can be by forming the possible future scenarios of supply and demand using a water supply network simulation model, which would include a probabilistic stream flow forecasting model as input under given operating rules, and then studying the likely outcomes.

Models for reservoir system operations have been developed in the past and are still in use (e.g. WATHNET, Kuczera G., 1997; IQQM, 1995; HEC-5, U.S. Army Corps Engineers, 1998; ACQUATOR, Oxford Scientific Software 2003 and REALM, Diment, G.A. 1991). However, models offering flexibility in terms of operating rules and computational time step, possessing relatively fast model run speed and supporting a large number of replicate inputs for reservoir reliability studies are rare.

In the following section, we describe the development of a new water balance model for this purpose.

2. THE WATER BALANCE MODEL

2.1 Theory

A water supply headworks system may involve one or more reservoirs for water storage, regulating downstream flow through release and supplying water to meet downstream demand as required. Each reservoir in the system receives inflows and produces outflows varying from period to period. Water budgets are balanced as water is routed through the system and individual reservoirs. The conservation of volume can be used to account for the overall system water balance and the water balance at individual reservoirs.

The basic conservation of volume equation for a reservoir or a river reach for a time interval Δt is expressed as

$$S_{t+\Delta t} - S_t = \sum_i I_{vol} - \sum_i O_{vol} \tag{1}$$

where S_t and $S_{t+\Delta t}$ are the storage volume at the beginning and end of the time interval Δ_t respectively, and $\sum I_{vol}$ and $\sum O_{vol}$ denote the total inflow and outflow volumes of a reservoir during the period of time interval Δ_t.

The term inflows in equation (1) include streams flowing into the reservoir, precipitation falling on the reservoir surface, subsurface flows into the reservoir, and return flows from the water use diversions. Outflows represent evaporation from the reservoir water surface, lakeside withdrawals, releases, spills and other losses etc.

Note that for a water supply system of several reservoirs equation (1) still applies. However the storage becomes total storage of the system which is the sum of all reservoir storages. The inflows become all inflows into the system of reservoirs. Typically, these inflows include all outflows from catchments and the precipitation falling on the reservoirs of the system. The outflows are replaced in equation (1) by total evaporation, total demand, total spilled water and total leakage from the entire network system.

The conservation of volume equation for a water supply system for an interval of time Δ_t can be expressed as follows

$$\begin{aligned} \sum_i S_{t+\Delta t} &= \sum_i S_t + \mathit{flows\ from\ catchments} \\ &+ \mathit{rain\,falls} - \mathit{demands} - \mathit{evaporations} \\ &- \mathit{spillwater} - \mathit{leakages} \end{aligned} \tag{2}$$

Evaporation from the water surface is typically a significant loss. In this model reservoir evaporation volume for each period is computed by multiplying an evaporation rate by an average water surface area during the time interval.

$$E_i = A_i e_i \qquad (3)$$

where E_i is evaporation volume from reservoir i during the time interval (unit: ML), e_i is evaporation rate (unit: mm) and A_i is average water surface (unit: km^2).

Reservoir water surface, A, is determined as a function of storage or is derived from a given set of area-elevation-storage data (see Chapter 5 in Wurbs, 1996). The following storage rating equation employed by WATHNET (Kuczera, 1997) is used in our model.

$$A = a + bV^c \qquad (4)$$

where V = storage/capacity, a, b, c and capacity are user-defined constants.

Equations (1) through (4) represent the fundamental concepts for water supply network simulation and are used to compute storage variation in the model. The various allocations of water to form the river/channel flows are determined subject to the given operating rules, downstream demands and water availability at the upstream node.

2.2 Operating Rules

Multiple-reservoir water supply network simulation is a complex task from the perspective of formulating operating rules. A good operating plan would ensure a reliable water supply. The new model developed in this study allows users to specify their own operating rules for the evaluation of the system behavior in response to such operating rules. However, a default set of operating rules is adopted by the model if user defined operating rules are not available.

The default operating rules assume a virtual storage for each non-reservoir node except for the termination node. A virtual storage of a node implies the net water available from the node. In the case of a reservoir, it has a virtual storage equal to its real storage. A virtual storage at a catchment node is defined as its outflow volume during the time interval. Virtual storage at other nodes is computed according to their upstream virtual storages. Figure 1 illustrates an example of how to calculate virtual storage for these nodes. In this figure virtual storage at node C is the upstream virtual storage Va multiplied by an arc weighting factor, which is always a fraction, being specified (by default) as the reciprocal of the total number of downstream arcs (exclude arcs that connect to the Termination node, which have zero value of the weighting factor) of the start node of the arc being considered. Similarly, virtual storage at node E is the sum of 1/3Va and 1/2Vb for this example. Note that for any node with downstream arcs that do not connect to the Termination node, the sum of all downstream arc weighting factors for that node always equals one. In practice, arc weighting factors are pre-calculated according to network structure and set as default values. Users can change these weighting factors, subject to the condition that the sum of all downstream arc weighting factors of a node must remain equal to unity. The introduction of arc weighting factors effectively prevents water at upstream nodes from being overdrawn in the model.

If there is leakage in the flow path, then virtual storage at the end node of the arc is further reduced by the amount of water lost in the arc.

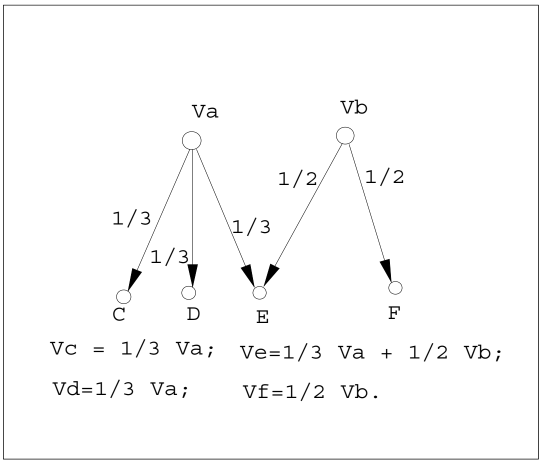

Figure 1: Example of virtual storage calculation

The order of assigning water to the river/channel goes from downstream to upstream. Water drawing from upstream nodes to a downstream node through the arcs is pre-defined as positively proportional to the product of upstream virtual storage and the corresponding arc weighting factor for that arc. An example of water assignment to the river/channel is illustrated in Figure 2. In this Figure, node "a" has two upstream arcs and two downstream arcs, respectively. O_1 and O_2 represent releases from node "a". The inflow I_1 and I_2 can be expressed as

$$I_1 = (O_1 + O_2) * (\tfrac{1}{2} * V_1) / V_a; \qquad (5)$$
$$I_2 = (O_1 + O_2) * (\tfrac{1}{2} * V_2) / V_a$$

where $V_a = \tfrac{1}{2} * V_1 + \tfrac{1}{2} * V_2$, and V_1 and V_2 are upstream node virtual storages.

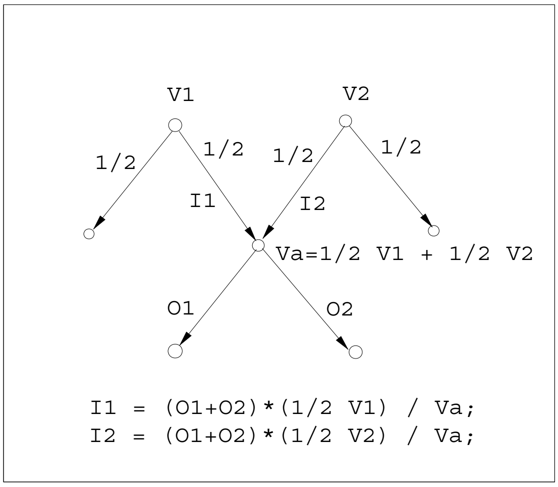

Figure 2: An illustration of water allocations

2.3 Numerical Techniques

Simulation of the water supply headworks system operations starts with the most downstream node, the demand center, routing up node by node until the water balance for the most upstream node, the catchment, is met. The model then starts a new route and the same procedures are repeated until the entire network is covered. During this process, water is assigned to each arc. The amount of water allocated to the river/channel is based on the operating rules described in section 2.2 as well as the downstream water use requirements and varies depending on the hierarchy of objectives. They are: (1) satisfy demand (may be reduced if water restrictions apply) at all demand zones; (2) satisfy instream flow requirements; (3) ensure that reservoirs are at their end of season target volumes.

For each time step, quantities are determined sequentially according to: 1. water assignment to river/channel; 2. compute storage at end of time step using conservation of volume equation; 3. determine spilled water by comparison of the calculated storage with full capacity storage for the same reservoir; 4. check system water balance using system water balance equation.

3. EXAMPLE OF MODEL APPLICATION

Sydney water supply headworks system is used for a preliminary model application. This system consists of nine reservoirs and two major demand zones, currently serving a population of approximate four million people in the region. Average annual consumption in 2000 is estimated as about 571000 ML water and is expected to grow to about 725000 ML by 2040 (Cui, 2005).

The main purpose of this study is to evaluate the performance and the ability of our model to simulate a multiple reservoir water supply system under given conditions. The operating rules and the hierarchical objectives used in this run are the default setting employed in the model as described in section 2.

A schematic of the Sydney water supply headworks system is presented in figure 3 (after SCA, 2003). The two major demand zones are further subdivided into ten demand zones. The solid lines represent pipelines/channels and the dotted lines are rivers/streams. The nodes marked with D and R, respectively, represent demand centers and reservoirs. Node J is a pipeline junction and node S represents a stream junction. Node W is a termination node that holds system waste water spilled from each reservoir. Some of the legend for fig. 3 is shown on Table 1. A pumping station at node 40 is placed between Tallowa Reservoir and Fitzroy Falls reservoir to lift water to Fitzroy Falls reservoir from which water is stored or transferred to Wingecarribee reservoir. This pump is triggered by a pump mark, expressed as a percentage of Warragamba storage capacity in this case.

For a multiple reservoir water supply system, water restriction may be triggered by the remaining storage in one or more reservoirs in a demand saving group. In this study, of nine reservoirs in the network, seven are selected to form a demand saving group. The pre-defined storage thresholds that trigger water restriction are presented in Table 2.

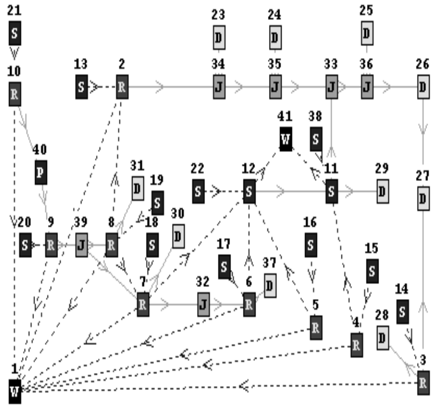

Figure 3: Schematic representation of Sydney water supply headworks system (after SCA, 2003). See Table 1 for key.

The hydro-climatic inputs were provided by SCA (Sydney Catchment Authority) in the format of a

WATHNET input file. A period of ninety years of historical record of reservoir inflow for nine reservoirs was retrieved and used for the model run. Evaporation and precipitation rates to the reservoir area use measured data obtained from Prospect reservoir for all reservoirs in this application.

Table 1: Reservoir's name and node number of Figure 3.

Reservoir Name	Node number	Demand saving group
Warragamba	2	yes
Woronora	3	yes
Cataract	4	yes
Cordeaux	5	yes
Avon	6	yes
Nepean	7	yes
Wingecarribee	8	yes
Fitzroy Falls	9	no
Tallowa	10	no

Table 2: Pre-defined system storage levels (% of full storage capacity) and corresponding demand reductions (% of full demand).

Water restriction	System storage	Demand reduction
Level 1	55 %	7 %
Level 2	45 %	12 %
Level 3	40 %	20 %
Level 4	35 %	30 %
Level 5	25 %	50 %

Reservoir full capacities and the parameters for storage rating equation (4) are listed in table 3. Non-reservoir nodes are assumed to have an insignificant storage. Initial storage for the model run is set to be full capacity for all nine reservoirs. The pump mark is set to be 65 % of Warragamba storage capacity.

Table 3: Reservoir full capacities and parameters for storage rating equations (After SCA, 2003)

Reservoir Name	Full Cap. (ML)	a	b	c
Warragamba	1,857,000	17.1	57.9	0.7555
Woronora	71,790	0.2	3.6	0.8196
Cataract	94,300	0.0	8.5	0.63
Cordeaux	93,635	0.0	7.8	0.75
Avon	146,700	5.06	5.49	0.8414
Nepean	40,810	1.85	1.4	0.87
Wingecarribee	24,100	1.19	5.07	0.572
Fitzroy Falls	10,000	4.1	1.13	0.758
Tallowa	36,000	5.7	1.21	0.926
Total	2,374,335			

Table 4: Annual demands used for the model application (obtained from SCA Wathnet model for year 1999)

Demand Center	Annual demand (ML)
Warragamba Township	1666
Orchard+Penr+BlueM	24244
Pr+North+Ryde+Liv.	252255
Sydney East demand zone	192152
Sutherland demand zone	19619
Helensburgh + woronora	14008
Macarthur Demand zone	36088
Picton + Bargo Demand Zone	3433
Bowral demand zone	3965
South Coast	52569
Total annual demand	599999

Demand inputs use annual demand (ML). Monthly demand is then obtained by multiplying annual demand by a seasonal weighting factor. A constant annual demand for each demand center for the period of simulation is assumed and their values are presented in Table 4.

4. RESULTS AND DISCUSSION

The model was run for a period of ninety years, starting in January 1909 and ending in December 1998, with a monthly time step and using a historical record of inflows. For the purpose of this simulation a full operational storage is assumed for each reservoir at the beginning of the simulation period. To simplify the modeling application, the dead water pools for all reservoirs are assumed to be zero. The conservation storage capacity is also set to be the full operational storage for each reservoir. Environmental flows and hydropower generation are not considered.

As mentioned in section 3, this study aims to evaluate the performance and the ability of our model to simulate water supply headworks system behaviors under a set of given conditions. A key consideration in relation to the model performance is model accuracy which is reflected in the system water balance. Theoretically, the system water balance, (as determined as all inflows – all outflows – system storage drawdown), must be equal to zero. In reality, the computational error accumulated during each operation results in a non-zero value. Figure 4 shows the bias in system water balance for the simulation period of ninety years with a monthly interval. It is clear from this figure that the bias of the system water balance falls in the range between -0.6 ML and 0.4 ML, with the majority close to zero. In comparison with the millions of

Mega liters of water stored in the water supply network system, this bias is significantly small. Therefore, it suggests that the model and the algorithm used in developing the model are accurate from the perspective of system water balance.

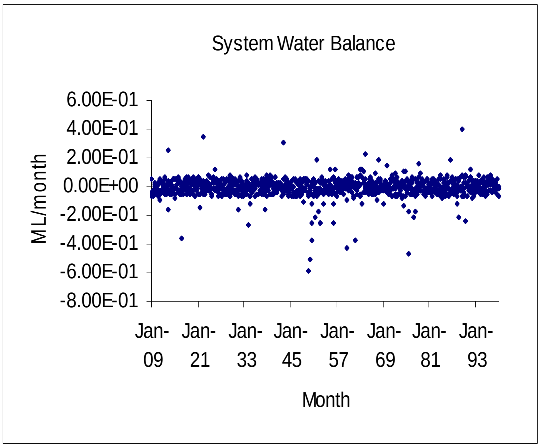

Figure 4: The bias of system water balance for the period of ninety years.

In addition, the model run speed represents another criterion for judging the performance of the model, in particular for modeling studies using a large number of replicates. A 0.25 second CPU time for a model run with a monthly time step for a period of ninety years has been recorded on a Pentium IV 3.0G Hz with 512 MB RAM, which means that a model run with 1000 replicates would need less than 5 minutes run time.

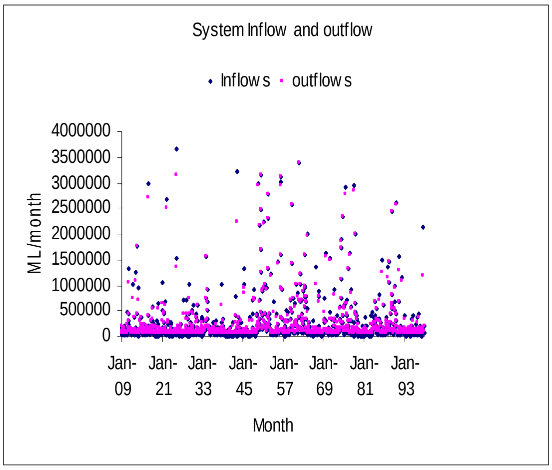

Figure 5: Total system inflow and outflow for the simulation period.

The system inflow and outflow rates for the simulation period are shown in Figure 5. From this Figure it is obvious that the distribution of the system outflow rate is relatively steady at a lower value while its higher values are accompanied by higher inflow rates. This is expected. As in normal hydrologic conditions or a drought period, the system outflow is mainly dominated by the requirements of the demand center, which are constant in this application. During the wet season higher inflow to the reservoir triggers water flow through the spillway. This in turn increases system outflow.

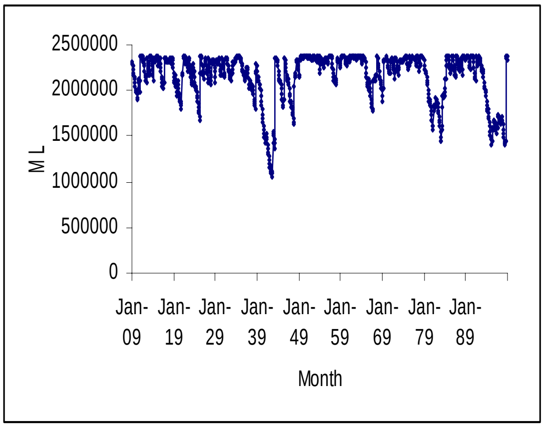

Figure 6: System storage varying with time

Table 5: Water restriction frequencies based on historical simulation and pre-defined storage thresholds.

Storage	Water Restrict.	Freq. %	Seas. Yr.	SOI Av. (year)
55<60%	No	0.93	11/1940 5-8/1941 10/1942 2/1995 4-6/1998	-15.27 (1940) -11.99 (1941) -12.22 (1994) -16.41 (1997)
45<55%	Level 1	1.11	9/1941 to 8/1942	-15.27 (1940) -11.99 (1941)
40<45%	Level 2	0.09	9/1942	-15.27 (1940) -11.99 (1941)

For a water supply headworks system, reservoir or multiple reservoir system storage represents an important quantity that reflects the ability of the system to satisfy a variety of water use requirements. The variations of system storage for the simulation period of 1909-1998 are presented in Figure 6. This figure shows several lowest points with the worst occurring around 1942, suggesting there was a prolonged drought lasting several years before heavy rain again filled the multiple-reservoir system storage.

Water restriction frequency is another important quantity in the multiple reservoir water supply system operations studies. It represents supply failure resulting in demand reduction and implies the possibility of supply failure if the given conditions are repeated in the future.

Table 5 presents such restriction frequencies based on historical simulation and pre-defined storage thresholds and the comparison with the Southern Oscillation Index (SOI), a commonly used indicator of the strength of an El Nino Southern Oscillation (ENSO) anomaly, an accepted cause of variability in rainfall in Australia. Clearly from this Table, all the water restriction events, including the events with storage between 55% and 60% of capacity which were assumed not to trigger water restrictions in this study, were closely related to strong El Nino events, pointing to the need of developing a probabilistic forecasting system that can predict such anomalies months in advance. It is also important to note that there were many other ENSO anomalies that did not result in significant storage depletions, and there were less significant storage depletions that were not linked to ENSO. This suggests a need for developing a probabilistic inflow forecasting system that is not specific to predicting ENSO linked anomalies, but can produce forecasts of droughts that consider a broader set of factors. A probabilistic forecasting system such as this is presented in Sharma (2000) and its coupling with the water supply simulation model would prove useful in water supply headworks planning studies. Development of such a forecasting scheme is one of the aims of this study.

5. CONCLUSION AND RECOMMENDATIONS

In this study, we presented a water balance model for the simulation and evaluation of water supply headworks system operations under given conditions and showed an example of model application. Full verification of the model was not carried out in this study due to the lack of appropriate long term historical data. Based on the analysis of the simulation results, the proposed model has been found capable of producing reasonable results in simulating multiple-reservoir system operations.

The next phase of development in this project includes development of a visualization interface for the animation of real time reservoir storages and stream flows, followed by the coupling with a multi-site probabilistic stream flow forecasting model.

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