Keynote: Multi-objective storages for flood mitigation and water resources development in small catchments

PEDRO SIMONE[1] & TREVOR M. DANIELL[2]

1 *Shared Watercourses Support Project, Administração Regional de Águas do Centro, 67 Sancho de Toar St. Beira, Mozambique*
simonepsimone@yahoo.com

2 *School of Civil, Environmental and Mining Engineering, The University of Adelaide, Adelaide, South Australia 5005, Australia*

Abstract In order to alleviate the continual increase in water demand over the available water resources, non-traditional water sources should be brought into the water supply cycle. Detention basins primarily designed for flood control have the potential to become part of this solution by delineating particular operational aspects. This paper proposes a framework for conjunctive use of detention basins for water supply purposes. An operational rule to ensure water supply without affecting the ability to control floods is developed. A study carried out found that this objective can be achieved through adopting a system of two levels of spills, where the first spill is aimed at ensuring continual release of inflows before the reservoir achieves full storage. The proposed approach was simulated using Monte Carlo analysis for Brown Hill Creek detention basins in Adelaide, South Australia, and satisfactory results were achieved.

Key words water; detention basins; flood control; sustainable yield; first spill level; risk management of water resources

INTRODUCTION

In the context of predicted increased water demand, driven by growing population over projected reduction of water resources in some regions due to the impact of climate change, it is important to bring alternative water sources into the water supply cycle. Conjunctive use of upstream storages for flood mitigation (detention basins), for water resources development purposes can help bring storm water sources into the water supply cycle. With detention basins primarily designed for flood mitigation purposes, being offline most of the time, there is a potential for using them to achieve conjunctive use requiring a multi-objective approach in their design and management.

Two major limitations can be identified within the available multi-objective models. Firstly, they rely on inflow forecasting that may lead to the following problems: (i) forecasting is not always accurate due to uncertainty characteristics of hydrological systems; (ii) in some regions; there are no forecasting systems in place. Secondly, almost none of them address small reservoirs in small catchments. These systems require a specific approach: under high variability of hydrological conditions, they can oscillate from empty to full stage and *vice versa*, in a short period of time, making them volatile to both failure to supply and failure to mitigate floods.

This paper provides a framework for optimisation of multi-objective reservoirs in small catchments which include flood mitigation objectives downstream. Within this framework, other objectives such as water supply, environmental maintenance and aesthetic purposes can be incorporated without compromising the primary objective of flood mitigation. The specific objectives of the study were: (a) development of a basic framework and an algorithm for optimization of multi-objective reservoirs in small catchments; and (b) validation of the algorithm by applying it to the Brown Hill Creek detention basins case study, in Adelaide, South Australia.

STUDY METHODOLOGY

Existing optimization models

Most of the existing multi-objective storages optimization models available in literature are designed to provide solutions for a particular storage purposes; however, their general philosophy is similar and includes: the definition of objective functions to be optimized; the identification of constraints;

ranking of objectives and constraints in order to define those that can or cannot be violated; and the use of computer software to develop solutions. The basic philosophy of multi-objective storage optimizations can be applied to small reservoirs in small catchments provided that their own specific design and operational aspects are addressed. The crucial point to consider for small reservoirs in small catchments is their volatility in moving from one state to another (full or empty) in a short period of time. Thus, time is a decisive factor for successful operation of these systems. The proposed framework and optimization algorithm are designed to ensure the systems' automatic response to inflow fluctuations during flood events, without the need for forecast data.

Proposed framework

The design and operation of detention basins are aimed at controlling floods downstream during storm events. For this reason, any attempt of their conjunctive use must ensure that there is no significant change in the basins' capacity to control their design peak flood. Under this scenario, the first objective, flood control, is set and then maximum yield is sought. The proposed framework includes the six steps indicated in Table 1.

Table 1 Proposed detention basins optimization framework.

Step	Description	Source of data
1	Streamflow statistical parameters assessment	Historical or generated flows
2	Preliminary yield estimation	Historical or generated flows
3	Assessment of flood mitigation requirements	Detention basin design parameters
4	Optimisation algorithm development	Existing optimisation models in literature
5	System optimisation under design flood	Design flood and preliminary yields
6	Final yield estimation	System optimisation outputs

Initially, preliminary yield estimation is made using statistical parameters assessed in step 1 (Table 1). Acceptable downstream maximum flow is then evaluated, defined by channel hydraulic capacity. The assessment of optimal operational parameters is made using the estimated yield in step 2 (Table 1) and the design flood obtained from flood mitigation requirements, step 3 (Table 1). Once the system is optimised to cope with its design flood, the outputs are applied to historical flows or generated data for final yield estimation, using behaviour simulation analysis. In step 4, an optimisation algorithm is developed and tested under design flood conditions, step 5 (Table 1). The parameters obtained from the optimisation process will ensure that the system will behave satisfactorily under the design flood; and thus, it will do so with smaller return period floods.

Proposed algorithm

The heart of the proposed algorithm is located in steps 2 and 3 (Fig. 1). After the definition of initial parameters, the system tests if the storage level is above the reference level. In the case of an affirmative answer, an additional release is activated. Initially, the additional release is defined as the excess volume of water above the reference level; however, this must satisfy the first and main objective function, flood control; consequently, the combined releases (normal supply and excess releases) with other unregulated flows cannot exceed the maximum flow to be accepted downstream (step 3, Fig. 1), and this is expressed by equation (1):

$$Q_T = Q_{BR} + Q_{NR} \leq Q\text{max} \tag{1}$$

where Q_T is downstream flow; Q_{BR} is flow released from detention basin; Q_{NR} is un-regulated flow; and Q_{max} is maximum flow capacity downstream. For small reservoirs in small catchments, the time interval (Δt) between subsequent release decisions is the crucial factor, because floods can rise in a matter of hours. For this reason, the time interval between two release decisions must be as short as possible to avoid accumulation of large volumes of water above the reference level during flood events. The maximum performance in terms of flood mitigation was found to be achieved when the decision to release excess volume is taken continuously, i.e. when $\Delta t \rightarrow 0$. Allowing a reservoir to have two spill levels: the first one located at the reference level and the second located at the top spillway level, leads to continuous decision-making in the field. Two types of first-level spills are proposed. For new detention basins, the spill intake system shown in Fig. 2 can be adopted, and for existing storages a siphon mechanism can be employed.

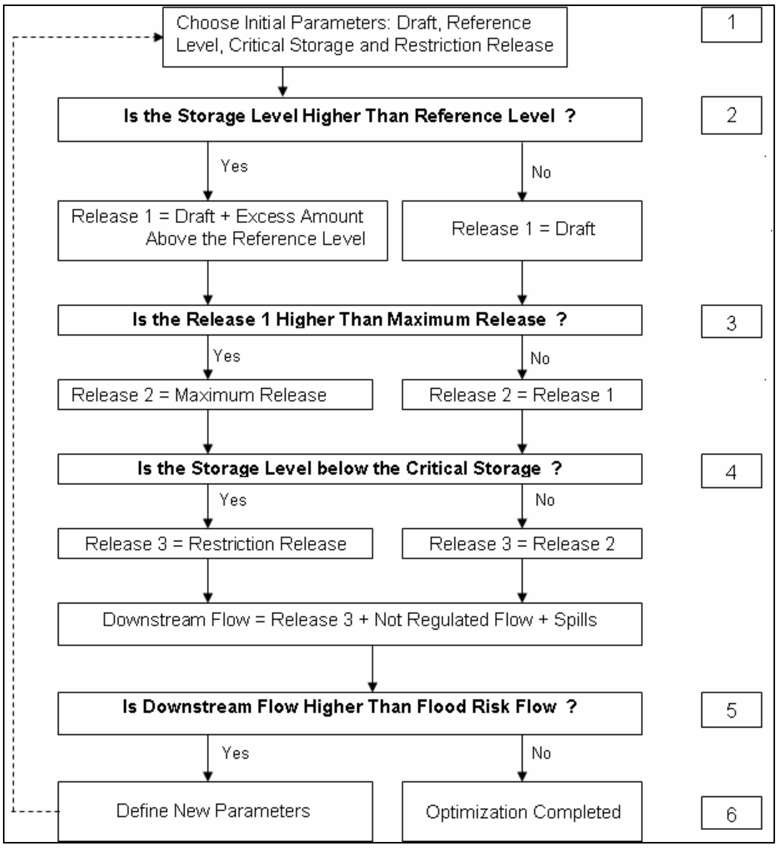

Fig. 1 Proposed algorithm scheme.

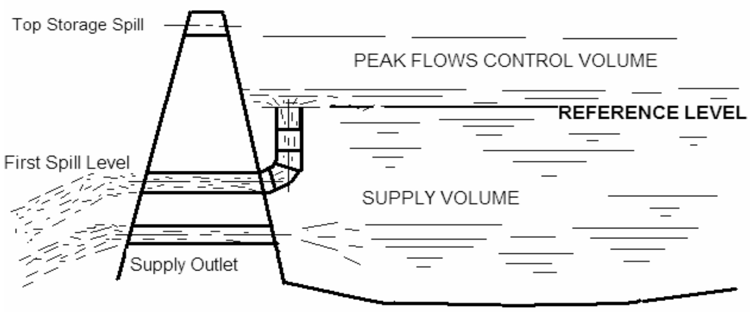

Fig. 2 Proposed first spill mechanism.

The proposed algorithm offers a multiple range of solutions. Firstly, it avoids the basin from reaching full storage, avoiding uncontrolled flows downstream. Secondly, the algorithm offers the opportunity to set other objectives. It can restrict releases when the critical storage is reached (step 4, Fig. 1). The desirable solution in step 6 is taken for the highest reference level that does not lead to failure to mitigate floods. This reference level is the main input used to estimate the maximum periodical yield from the system (second objective function), as per equation (2). Behaviour analysis with either historical flows or generated data can be used for the final yield estimation; nevertheless, more accurate estimation is obtained from shorter time intervals in subsequent data.

$$\max \ (Q_D) = F(V_{RL}) \tag{2}$$

where Q_D is potential yield and V_{RL} is reference level volume.

Algorithm strengths and limitations

The combination of the proposed algorithm and release mechanism has the following advantages:

(i) the system does not require forecasted data;
(ii) it provides flexible response to adverse hydrological conditions and is adjustable to new parameters; and
(iii) the system is easy to operate (it does not require constant supervision and does not require high qualified operators), and the operation process does not require power supply; thus it is environmental friendly, at least at the operational stage.

The main disadvantage is that the system operates with fixed parameters. It does not provide promptness of response to irregular distributions of rainfall between regulated and unregulated portions of the catchment, and to rainfall forecasting. This may lead to a release of excess water that could be capitalized on for future supply. Nevertheless, this approach ensures the system operation is on the conservative side, in terms of flood control.

RESULTS AND DISCUSSION

The proposed algorithm was applied to the Brown Hill Creek detention basins to assess optimum parameters for the projected conjunctive use of the proposed detention basins.

Study area characterization

Brown Hill Creek located in Adelaide, South Australia (as indicated in Fig. 3) rises in the Mount Lofty Ranges and discharges onto the Adelaide plains. The Creek has a total catchment area of

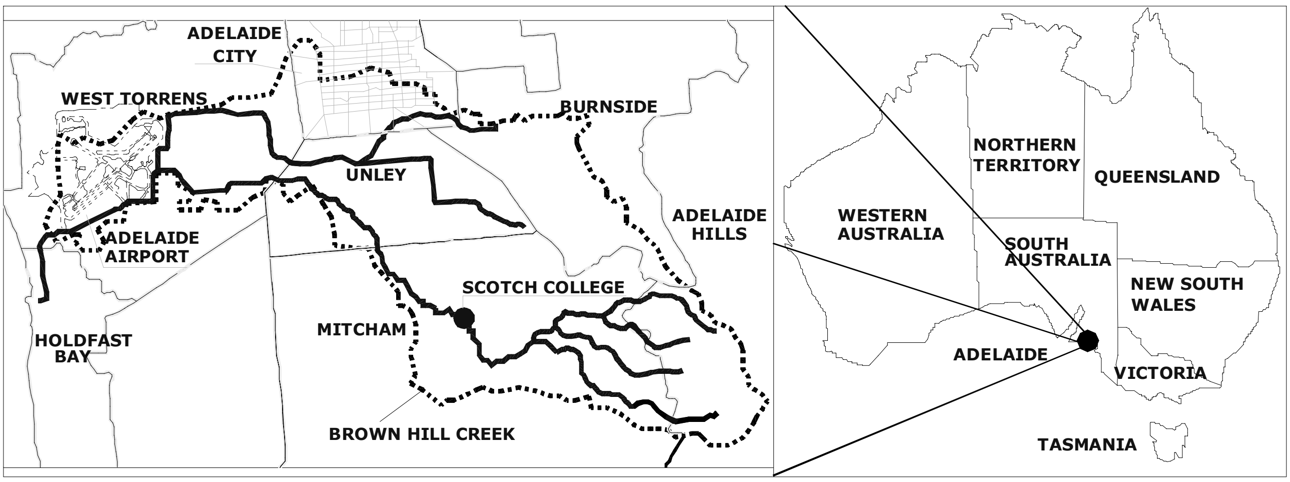

Fig. 3 Brown Hill Creek location in Adelaide, South Australia. Map not to scale (Source: adapted from Google Maps; Hydro Tasmania, 2006).

32.0 km^2 upstream of the Adelaide Airport (Hydro Tasmania, 2006). Flood risks from Brown Hill Creek are a subject of concern with a long history of flooding issues. Its path traverses a considerable developed section of the Adelaide Metropolitan area. However, the catchment, almost 18.3 km^2, upstream of Scotch College gauging station (Barnett, 1998) has mainly rural characteristics and offers opportunities for temporary storage of flood flows. A master plan study was undertaken following a flood in 2005 which recommended, among other measures, the construction of two detention basins with storage capacities of 370 ML (detention basin II) and 60 ML (detention basin IV). The proposed storages are projected to regulate 68% of the total upper catchment flow, to be used mainly for aquifer storage recharge and recovery (ASR).

System analysis

The application of the algorithm to the proposed detention basins followed the steps below:

(i) assessment of the streamflow statistical parameters using 17 years of streamflow data from the Scotch College gauging station supplied by the Bureau of Meteorology (ABM, 2009);

(ii) preliminary yield assessment (sustainable yield) using preliminary techniques, defined by McMahon & Mein (1978), namely: Gould Gamma method and McMahon's empirical;

(iii) assessment of flood mitigation parameters, defined by the downstream channel capacity, previous studies results were used, namely Hydro Tasmania (2006) and GHD (2008);

(iv) the system's performance assessment, by testing the implication of each parameter on system capacity to control floods *versus* the potential yield.

Statistical parameters

Brown Hill Creek statistical values are shown in Table 2 and the flow duration curve in Fig. 4, which suggest that the system faces cyclic droughts and floods. It was found that the flow distribution is greater in winter and spring, with minimum values observed in summer months. Sustainable yields were estimated on a seasonal basis with the following yields relative to mean monthly flow obtained: summer, 19%; autumn, 31.5%; winter, 189%; and spring, 159%.

Table 2 Brown Hill Creek statistical parameters.

Parameters	Annual	Monthly	Weekly	Daily
Mean flow (ML)	2187.53	182.29	47.82	6.81
Standard deviation	1293.44	286.40	95.40	26.87
Coeff. of variation	0.59	1.57	1.99	2.48
Coeff. skewness	1.33	3.33	4.92	9.97

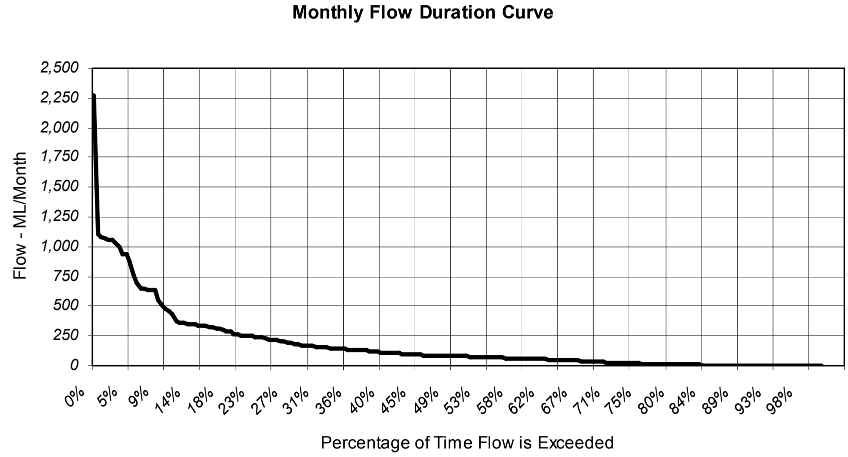

Fig. 4 Brown Hill Creek flow duration curve.

Yield estimation

Preliminary yield estimation shows that without assuming the need to mitigate floods, the following results were obtained: Gould Gamma method, 713 ML/year, and McMahon's empirical equation, 654 ML/year. These values are above 40% of the total regulated flow. It should be noted that the distribution of the yield is not homogeneous through the year. It follows the pattern of the streamflow characteristics leading to more aquifer recharge in winter and spring than in summer and autumn.

Optimisation algorithm application

The optimisation algorithm was used to assess the system performance using behaviour simulation under the design flood. It is assumed that once the system responds satisfactorily to the design flood, it will do so under smaller return period floods. As the main objective of this study was the assessment of the risks associated with conjunctive use of detention basins for water supply and other purposes, a comparative analysis was made. Firstly, the system performance was assessed without incorporating conjunctive use of the basins, and then the impact of conjunctive use was tested. The characteristics of the design flood are given in Table 3. The shortest peak flood time-step available was 15 minutes. The flood routing results for the predicted critical flood without conjunctive use of the basins indicated that the detention basins will reduce the peak flow from almost 27 m^3/s to 11.0 m^3/s. This confirms that the detention basins were designed to reduce peak flows to less than 13.1 m^3/s at the Scotch College gauging station.

The assessment of the system performance under the design flood, with conjunctive use and applying the proposed algorithm was made for different reference levels. The results were applied in a daily historical behaviour analysis in order to assess their implications to the potential yield.

The comprehensive summary of comparative results is shown in Table 4.

Table 3 Summary of the system optimization parameters.

Parameter	Units	Value
Critical ARI period	Years	100
Critical ARI duration	Hours	36
Critical flood peak flow	m^3/s	27.2
Critical flood hydrograph volume (in 36 hours)	ML	1601.7
Maximum downstream channel capacity assumed	m^3/s	11.0
Critical storage as a proportion of the total storage	%	10.0
Restriction release proportionally to average flow	%	19%

Table 4 System response to the design flood.

Reference level (% total storage)	Max downstream flow (m^3/s)	Potential yield (ML/year)	Prob. failure to supply
10.0	10.12	688.5	8.0%
20.0	10.12	873.4	7.0%
30.0	10.12	918.8	7.0%
40.0	10.52	952.7	6.0%
42.5	10.59	959.7	6.0%
47.5	11.22	967.2	6.0%
45.0	12.14	967.2	6.0%
50.0	12.56	981.3	6.0%
60.0	13.81	1005.8	4.0%

The results in Table 4 show that the maximum reference level ensuring the system safety to control floods downstream is at 42.5% of the total storage volume. The potential yield achieved is equivalent to 64% of the mean annual regulated flow, which is close to 70%, the maximum divertible yield from conventional storage according to McMahon & Mein (1986). The estimated annual yield can potentially cover garden watering water demand for 8500 houses.

SUMMARY AND RECOMMENDATIONS

This paper presented an alternative approach for small multi-objective storage optimisation, particularly aimed at maintaining downstream peak floods under control. The study undertaken in this context found that improving existing general multi-objective storage basic techniques, by adopting automatic releases according to storage level, is an important approach for conjunctive use of detention basins. The main advantage of the proposed "first spill level release" approach is its ability to continuously respond to high flows without the need for flow forecasting, or a sophisticated operational system, and does not require energy consumption.

The approach was simulated for the proposed Brown Hill Creek's detention basins with satisfactory results. Overall, these research findings are an important step for bringing storm water into the water supply cycle in a sustainable way where potential for detention basins exists.

REFERENCES

ABM (2009) Weather station data. http://www.bom.gov.au/climate/data/weather-data.shtml (accessed on 24 August 2009).

Barnett, S. R. (1998) Mount Lofty Ranges groundwater assessment – Brown Hill Creek catchment. Primary Industry and Resources SA, Adelaide, Australia.

GHD (2008) Brown Hill Keswick Creek stormwater project: preliminary assessment of flood detention basins on Brown Hill Creek – Report for stage 1, Adelaide, October 2008.

Hydro Tasmania (2006) Brown Hill and Keswick Creeks flood mitigation study: flood management master plan – Report – 003 Rev 0. Hydro Tasmania Consulting/AWE/QED, Adelaide, South Australia, Australia.

McMahon, T. A. & Mein, R. G. (1978) *Reservoir Capacity and Yield*. Elsevier Scientific Publishing Company, Amsterdam, The Netherlands.

McMahon, T. A. & Mein, R. G. (1986) *River and Reservoir Yield*. Water Resources Publications, Colorado, USA.

SA WATER (2009) *A Thirst for Change: Water Proofing Adelaide.* Adelaide, SA Water, Australia.