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Decision support for the selection of water release strategies at open-air irrigation reservoirs

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Abstract

Water earmarked for irrigation purposes in the agricultural sector is typically stored in open-air reservoirs. The availability of irrigation water greatly impacts the profitability of this sector and this availability is largely determined by prudent decisions related to water release strategies at open-air reservoirs. The release strategy for an open-air irrigation reservoir is typically decided upon by a board of management at the start of the hydrological year. The selection of such a strategy is difficult, since the objectives which should be pursued are not generally agreed upon and unpredictable weather patterns cause reservoir inflows to vary substantially between hydrological years. A mathematical model is proposed in this paper which may form the basis of a decision support system for the selection of a beneficial water release strategy. Based on historical data, the proposed model generates a probability distribution of the reservoir volume at the end of a hydrological year for a given initial water release strategy and stochastically simulated reservoir inflows. The initial strategy is dictated by irrigation demands and reservoir sluice parameters. This strategy is then adjusted iteratively, with the aim of centring the hydrological year end volume distribution on some target value. Adjustments are made according to user-specified weight factors, which represent the demand satisfaction importance of the various decision periods. The repeatability of a given water release strategy is taken to depend on an estimate of the most likely reservoir volume at the end of the hydrological year as a result of this strategy. The probability of water shortage for a given transition volume may be determined using this model by equating the start and end volumes for simulated hydrological years. This information allows for the computation of acceptable tradeoff decisions between the fulfilment of the current hydrological year's demand and the future repeatability of a release strategy.

1 Introduction

Water is one of the most important resources for the sustenance of life on planet earth. Other than its immediate and most obvious use as drinking water, the applications of this resource in human endeavour are extensive. According to the World Economic Forum

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2015 [7], water crisis is the number one global risk, based on impact to society. The success of many economic systems depends on the continual availability of water.

The portion of the crop farming industry which makes use of irrigation is one such system. This industry depends on the availability of water for its livelihood. Since precipitation periods and river flows are dynamic, volatile in some cases and do not necessarily overlap with demand periods, water must typically be stored to meet irrigation demands. Open-air water reservoirs are most commonly used for this purpose in South Africa.

Water shortages or flood damage may occur downstream from irrigation reservoirs with disastrous effects for the farmers in the region if reservoir levels are not carefully controlled. Thus, an effective release strategy must be employed for beneficial reservoir level control. The release strategy for an open-air irrigation reservoir is typically decided upon either by a formal board or by an informal group of farmers at the start of the hydrological year.

Keerom Dam is an excellent example of an open-air reservoir with the primary purpose of supplying water for irrigation purposes. It is the second largest privately owned open-air reservoir in South Africa and is situated in the Nuy agricultural irrigation district, north-east of Worcester, in the Western Cape. The reservoir's wall height from dam crest to river bed level is 38 meters and when at maximum storage capacity the water surface area is 92 hectares. Nineteen farmers benefit from its water supply, of which six serve on the Nuy irrigation board. This board determines the release strategy for the reservoir on an annual basis.

The best choice of release strategy is not an obvious one for four reasons. Firstly, the objectives which should be met by such a strategy are not generally agreed upon. Irrigation demands should be met, while the risk of water shortage and/or the risk of flood damage may be minimised, or evaporation losses may be minimised. Secondly, unpredictable weather patterns cause reservoir inflows to vary substantially between hydrological years, thus making planning and water allocation exceedingly difficult. Thirdly, the calculation of irrigation demands is a non-trivial problem, which is influenced by the climate as well as the distribution of crop types under irrigation and various agricultural policies. Finally, the persons responsible for the selection of a release strategy may differ vastly in their attitude toward risk, which plays a critical role in the selection of a consensus strategy.

In this paper, a mathematical model is proposed which may form the basis of a decision support system for the selection of a beneficial water release strategy. The risk related to a given strategy is quantified in the model, so as to accommodate tradeoff decisions between the fulfilment of the current hydrological year's demand and future repeatability of good strategies.

This paper is organised as follows. First a brief literature review pertaining to existing models for reservoir operation is given in §2, after which the assumptions made in the development of the model proposed in this paper are listed and motivated in §3. A framework of our modelling approach, depicting the required inputs, processes and information flows is supplied in §4, after which the relevant processes are described in more detail. More specifically, the simulation of inflows is described in §5, after which the method proposed for generating period volume distributions is discussed in §6. A method for the quantification of risk is described next in §7, before concluding remarks are made in §8.

2 Literature Review

In this section, previous models built for irrigation reservoir operation decision support are described in general, after which the focus shifts to a description and evaluation of the models which have previously been implemented at Keerom Dam specifically.

Mathematical models which have been implemented in support of the formulation of good water release strategies for open-air reservoirs can be partitioned into the classes of deterministic optimisation models on the one hand and stochastic simulation and optimisation models on the other.

Several stochastic modelling approaches have been implemented in the context of reservoir operation management. A stochastic linear programming model was, for example, developed by Loucks [2]. According to Yeh [11], this formulation suffers from the problem of dimensionality since its constraints may easily exceed several thousands in real-life applications.

Dynamic programming models are very popular for analysing complex water resource problems because of their ability to incorporate the non-linear and stochastic aspects of these problems into the formulation [11]. Butcher [1] successfully applied a stochastic dynamic programming approach to a multi-purpose reservoir.

More recently, non-linear multi-objective models have been applied in the context of reservoir management problems and these models have been solved using evolutionary algorithms. Reddy & Kumar [4] used this approach to obtain tradeoff release strategies for the multi-purpose Bhadra reservoir system in India, which is used for irrigation and hydro electricity generation. The point by point search approach utilised by traditional optimisation methods are inappropriate for multi-objective optimisation, since these methods produce a single optimal solution. Open-air reservoir operation necessarily involves tradeoff decisions; it may therefore be beneficial to supply more than one solution option to the managers of such reservoirs.

Artificial Neural Networks (ANNs) have been utilised for the simulation of reservoir inflows and for determining release strategies [3]. ANNs is a class of artificial intelligence techniques which mimic the behaviour of neuron connections in the brain. An interconnected set of nodes, called neurons, are organised in input, hidden and output layers. The connections between nodes each has a certain weight, representing the strength of the connection. An ANN learns, much like a biological brain, through the strengthening of connections between selected neurons, by experience. Historical, verified data are fed into the input neurons of the network, after which the output is observed and the weights of the neuron connections are adjusted with the aim of decreasing the deviation of the network output from the historically observed values. This approach works well in the context of reservoir management, even for a limited amount of data in the presence of irregular seasonal variation, is robust and is faster than conventional approaches [3].

Previous models applied to Keerom Dam include a deterministic linear programming model developed for incorporation into a flexible decision support system called ORMADSS (an acronym for *Optimal Reservoir Management Active Decision Support*), by Van Vuuren & Gründlingh [10]. In their model the objective is to obtain an optimal release strategy for average years, serving as input to the DSS, by

$$\text{minimising} \sum_{i \in \mathcal{T}} E_i(V_i, V_t), \quad t \equiv i-1 \,(\mathrm{mod}\, T), \quad \mathcal{T} = \{0, 1, \ldots, T-1\}$$

subject to

$$\begin{aligned}
\left(1 - \frac{ke_i}{2}\right) V_t - \left(1 + \frac{ke_i}{2}\right) &\geq q_i - I_i + e_i c, && i \in \mathcal{T},\ t \equiv i-1 \,(\mathrm{mod}\, T),\\
\left(1 - \frac{ke_i}{2}\right) V_t - \left(1 + \frac{ke_i}{2}\right) &\leq Q_i - I_i + e_i c, && i \in \mathcal{T},\ t \equiv i-1 \,(\mathrm{mod}\, T),\\
V_i &\geq rV_{\max} && i \in \mathcal{T},\\
V_i &\leq V_{\max} - V_i && i \in \mathcal{T},
\end{aligned}$$

where E_i denotes an evaporation loss function of the reservoir volume V_i, I_i denotes the net volume inflow, e_i denotes the evaporation rate, and q_i and Q_i denote respectively lower and upper bounds on the expected amount of water during period i. Furthermore, k is a constant of proportionality between reservoir volume and water surface area, c is an offset constant, r denotes a safety risk factor between zero and one, and $V_{\max}$ denotes the maximum reservoir storage capacity, before overflow occurs. According to Cheng and Rezicek [5], deterministic models which are based on average or mean stream flows may, however, result in overly optimistic release policies.

Strauss [8] criticised the simplistic manner in which Van Vuuren & Grundlingh [10] accommodated risk by only including a minimum reserve for the operating level of the reservoir, while not directly allowing for the possibility of unmet demand. Strauss implemented a very similar model, together with the additional risk-related constraint

$$\alpha D_i \leq B_i \leq \min\{(1+\alpha)D_i, B^{\max}\}, \quad i \in \mathcal{T},$$

where D_i and B_i denote respectively the demand and release during period i, to ensure that demand is met to within a certain variation parameter α. It is important to note that risk was, however, not quantified in the model of Strauss.

Quantifying the representation of risk is a crucial element lacking in the two models reviewed above. Furthermore, models which provide a single optimal solution may be insufficient, since reservoir operation commonly involves tradeoff decision options, as mentioned above. As a response, multi-objective models have often been implemented in the context of reservoir management, as mentioned. This works well for complex, multi-purpose reservoir systems with multiple decision variables and complex benefit functions, whereas for single-purpose reservoirs, only two directly conflicting objectives exist, and the decision options depend on a single variable, namely sluice control.

3 Modelling Assumptions

The farmers who benefit from Keerom Dam are in agreement that the release of more water (up to maximum sluice capacity, thus not including floods) is more beneficial than the release of less water. It may generally be assumed that the benefit function for normal operation of an irrigation reservoir is a strictly increasing function. This assumption makes the problem of determining a suitable release strategy fairly simple: release the maximum amount of water, keeping in mind the risk of not being able to achieve repeatability of the strategy over successive hydrological years. The focus of a reservoir release model should therefore be on quantifying the risk related to a given release strategy, rather than merely searching for an optimal strategy or set of strategies.

In order to develop a mathematical model for irrigation reservoir operation which incorporates a quantification of risk, the following assumptions are made:

I *Irrigation reservoir.* The model will be designed for use in the context of open-air reservoirs used for irrigation purposes only. Release strategy formulation will not be considered for reservoirs designed for other uses (such as for the storage of drinking water or the generation of hydro-electricity).

II *Time continuum discretization.* The scheduling horizon over which a release strategy is to be determined will be discretized into a number of time intervals, called *decision periods*, which are typically weeks or fortnights.

III *Evaporation rate.* The evaporation rate during a given decision period will be considered to be directly proportional to the average exposed water surface area of the reservoir and thus a function of the average reservoir volume during that period. The coefficient of proportionality will be taken to depend on the historical meteorological conditions of the time interval in question. For relatively short decision periods (*e.g.* weeks) this is a realistic assumption. The South African Department of Water Affairs and Forestry keeps a database of all water reservoirs exceeding a certain minimum storage capacity, which includes historical daily evaporation losses. For new reservoirs, the evaporation rates of older reservoirs in the vicinity may be used as an initial estimate.

IV *Repeatability.* The repeatability of a given water release strategy will be taken to depend on an estimate of the most likely reservoir volume at the end of the hydrological year as a result of this strategy. Thus, the reservoir volume during the transition between hydrological years is used as the measure of future repeatability.

V *Silting rate.* The silting rate is the rate at which the reservoir's capacity is reduced by the accumulation of sediments in the reservoir. This rate will be considered negligibly small. We consider the formulation of release strategies over planning horizons not exceeding one year in this paper. The notion of repeatability is incorporated to ensure that a reasonable starting volume is available at the start of the following year, when planning will commence for that year. Changes in reservoir volume due to silting can thus be taken into account on an annual basis. For such scheduling windows this is a realistic assumption.

VI *Seepage rate.* Seepage is the escape of water into the reservoir floor. Because it is very difficult to measure this kind of water loss rate separately, it is assumed that the seepage rate is included in the reservoir's net influx.

VII *Demand.* The water demand during a specific decision period is assumed to be constant. For relatively short decision periods (*e.g.* weeks) this is a realistic assumption.

VIII *Conservation law.* It is assumed that the change in water volume during a given decision period equals the net influx (including all the reservoir's water sources, precipitation into the reservoir and its catchment area, as well as seepage losses), less evaporation losses and all reservoir outflows, including controlled sluice outflow and overflow.

4 Modelling Framework

The framework depicted in Figure 1 partitions the inputs of the model into historical data, as well as various user-inputs and reservoir-related parameters. Historical data refer to past inflows, to be utilised in the simulation of future inflows, and past evaporation losses used to estimate the coefficient of proportionality of evaporation during any given decision period.

The required user-inputs are the decision period length (typically weekly or biweekly), the number of remaining decision periods in the hydrological year, the current reservoir volume and some target end-of-hydrological-year volume (a target volume corresponding to a certain level of risk should be computed and suggested to the user, but this value should be user-adjustable). The weekly demand profile, which may be computed using standard irrigation decision support software, such as *CROPWAT* [9], is also considered a user-input.

Reservoir-related parameters include the maximum sluice release capacity, the minimum allowed release volume per decision period according to legal requirements, the reservoir's storage capacity and its shape characteristic, which relates the water level, stored water volume and exposed water surface area of the reservoir. The processes and information flows in Figure 1 are described in some detail in the following sections. The process to be conducted first, before the model execution, is the simulation of inflows.

5 Monte Carlo Simulation of Inflows

The historical inflows will be used to obtain the cumulative inflow distribution for each simulation period in the year. The simulation period length may be daily, weekly, biweekly or monthly, but must be shorter than or equal to the decision period length. Visualising the cumulative distribution plot, historical net inflow for a given period may be placed in bins on a horizontal axis, with each bin containing the number of historical inflows less than the bin's upper limit, and where the vertical axis then denotes the number of inflow data points. The vertical axis may be normalised, to represent portion of total inflows.

The South African Department of Water Affairs and Forestry's database includes daily inflows, typically resulting in ample historical data. This allows for accurate distributions to be obtained. In other words, it is usually not required to fit a theoretical distribution to the data — the empirically obtained distributions may be utilised directly. For a

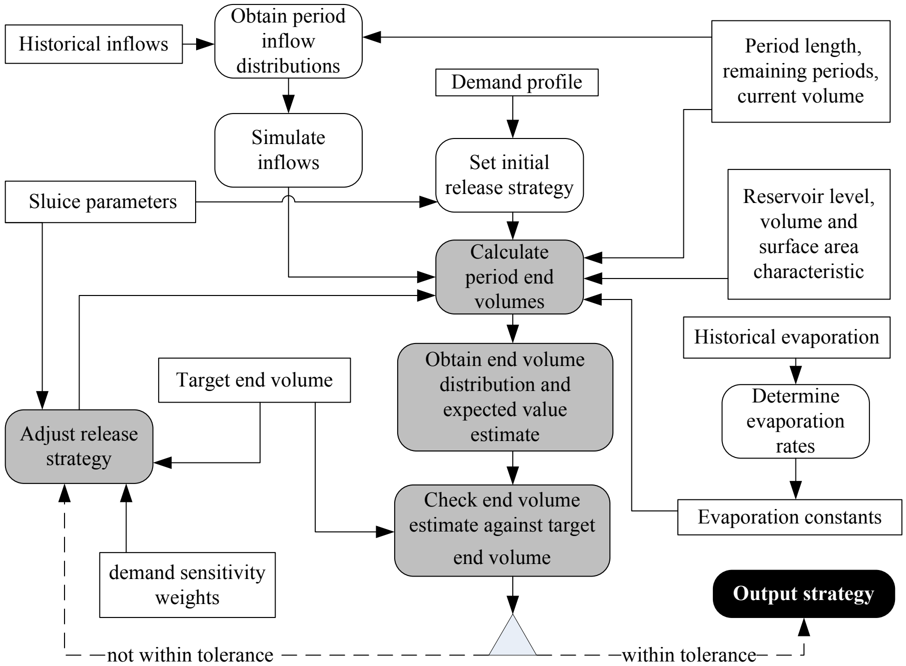

Figure 1: *A framework depicting the processes and flows of information in the proposed model.*

newly built reservoir the prediction of future inflows, without any historical data, would constitute a challenging separate research project.

Based on these distributions, the Monte Carlo method may be utilised in conjunction with the inverse transform method, to simulate inflows. The inverse transform method relies on the probability integral transformation, as described by Rizzo [6].

Let I_t be the net reservoir inflow during decision period t and let U be a uniform random variable on the interval $[0, 1]$. If I_t has the cumulative distribution function F_{I_t}, then $F_{I_t}^{-1}(U)$ has the same distribution as I_t. An instance of I_t may therefore be simulated according to the inverse transform method by generating a uniform $[0, 1]$ variate u and recording the value $F_{I_t}^{-1}(u)$. Once this has been done for each simulation period, the inflows of a single hydrological year have been simulated. A large number of parallel years (one thousand, for example) may thus be simulated.

6 Obtaining Period Volume Distributions

Let V_t denote the reservoir volume at the end of decision period t, x_t the water volume released during decision period t, E_t the volume of water lost due to evaporation during decision period t, e_t the evaporation rate per unit of average exposed water surface area during decision period t, and A_t the exposed water surface area at the end of decision period t, where $t \in \mathcal{T}$, for some set $\mathcal{T} = \{0, 1, \ldots, T-1\}$ of decision periods. According to

Assumption VIII of §3 it follows that

$$V_t = V_{t-1(\mathrm{mod}\,T)} + I_t - x_t - E_t, \quad t \in \mathcal{T},$$

while according to *Assumption III* it follows that

$$E_t = e_t\left(\frac{A_{t-1(\mathrm{mod}\,T)} + A_t}{2}\right), \quad t \in \mathcal{T}.$$

Furthermore, the exposed surface area of the reservoir is related to the stored water volume according to some reservoir shape characteristic f in the sense that

$$A_t = f(V_t), \quad t \in \mathcal{T}.$$

A preliminary release strategy may be determined according to the demand profile and the sluice release parameters. Let D_t denote the water demand during decision period t and let $x_{\min}$ and $x_{\max}$ denote respectively the minimum and maximum possible release volumes during any decision period. Then

$$x_t = \begin{cases} x_{\max} & \text{if } D_t \geq x_{\max}, \\ D_t & \text{if } D_t \in (x_{\min}, x_{\max}), \\ x_{\min} & \text{if } D_t \leq x_{\min}, \end{cases}$$

for all $t \in \mathcal{T}$.

Using the current reservoir volume, the stochastically simulated inflows for the remaining decision periods of the hydrological year and the preliminary release strategy described above, a distribution of the reservoir volume at the end of the hydrological year, resulting from this strategy, may be obtained. This distribution may be analysed, using standard statistical methods for inference, to obtain an estimate of the expected reservoir end volume

$$\mu_{V_T} = \frac{\sum_{j=1}^{K} V_j^*}{K} \approx \sum_{i=1}^{S} y_i \overline{V_i^*}, \tag{1}$$

where K denotes the number of simulation replications and V_j^* denotes the end volume obtained by simulation replication j. This estimate may be compared to the expected end volume, as obtained from the distribution, to asses the effect of the distribution's bin sizes. In (1), S denotes the number of bins used to obtain the empirical distribution, y_i denotes the proportion of end volumes residing within bin number i, and $\overline{V_i^*}$ represents the midpoint between the upper and lower limits of bin i.

The estimate μ_{V_T} will be compared to a target end volume specified by the decision maker. If the estimator falls outside a certain tolerance band centred around the target value (also specified by the decision maker), the release strategy should be adjusted with the aim of centring the end volume distribution on the target value.

In our model, seven factors are taken into account for this adjustment: the number of remaining decision periods, denoted by n, the end volume estimate μ_{V_T} in (1), the target end volume, denoted by V_A^*, a tolerance $\alpha \in (0, 1]$ within which the target end volume should be met, the minimum and maximum sluice release parameters, and user-specified weight factors which represent each demand period's sensitivity to not meeting water demand for that period, denoted by $w_t \in [0,\, 1]$, where a lower value represents a more sensitive period. Let μ_w denote the mean of the user-defined weight factors. Our proposed adjustment process of the preliminary release strategy is iterative in nature. Each iteration of this process is accomplished in two stages. First

$$x_t' = x_t + \left(\frac{\mu_{V_T} - V_A^*}{n}\right) \times \frac{w_t}{\mu_w}$$

is computed, after which

$$x_t'' = \begin{cases} x_{\max} & \text{if } x_t' \geq x_{\max}, \\ x_t' & \text{if } x_t' \in (x_{\min},\, x_{\max}), \\ x_{\min} & \text{if } x_t' \leq x_{\min} \end{cases}$$

is determined for each remaining decision period t. Periods with sensitive demand are also expected to be periods of higher demand. By definition, the first strategy satisfies demand as well as possible, and thus larger releases are made during sensitive periods, possibly equalling the maximum release capacity. If the end volume estimate exceeds $(1+\alpha)V_A^*$, more water will be released during less sensitive periods than sensitive ones, so as to expedite the centring of the distribution. If the end volume estimate is less than $(1-\alpha)V_A^*$, the water volume released during non-sensitive decision periods will be decreased in greater proportions than the water volume released during sensitive periods, so as to ensure that demand is met as best possible.

During each iteration of this adjustment procedure, the end volume distribution is recalculated and a new end volume estimate obtained, closer to the target value, until the estimate falls within the interval $[(1-\alpha)V_A^*, (1+\alpha)V_A^*]$. Once the distribution is thus centred on the target value, the current release strategy may be used as starting point for developing tradeoff strategy suggestions.

7 Quantifying Risk

According to *Assumption VII* of §3, the repeatability of a strategy is taken to depend on the reservoir volume during the transition between hydrological years. The probability of water shortage associated with reservoir volumes during this transition may be determined by equating the starting and target volumes in the model, for a simulated hydrological year, and solving the model for a range of volumes. The number and sizes of shortage occurrences may then be obtained by comparing the release strategy for a given reservoir transition volume with the demand profile. An expected percentage of unmet demand may then be associated with a given transition volume.

In any period during an actual hydrological year, the probability of ending at a certain volume may be obtained from the end volume probability distribution resulting from the current release strategy. The percentage of expected unmet demand during subsequent years, related to this volume, will have been obtained by the approach described in the previous two sections. The risk of not meeting future hydrological years' demand as a result of a current strategy, can therefore be expressed numerically.

In the case of a dry year, when the notion of risk requires special attention, tradeoff decisions between the fulfilment of the current year's demand and future repeatability may be required. Future repeatability here refers to a level of confidence in the ability to repeatedly fulfil the irrigation demands of subsequent years. If, due to particularly low reservoir storage levels during a dry year, the proposed strategy which centres the end volume distribution on the specified target value for repeatability to within the acceptable tolerance interval fails to meet the current year's demand adequately, the decision maker may prefer to aim for a lower target ending volume. The fulfilment of the current year's demand will thereby be improved, but at the cost of a decrease in the security of future years' water supply. The improvement in demand fulfilment, as well as the decrease in security, may finally be quantified and compared.

8 Conclusion

A water release model, which may form the basis of a DSS for open-air irrigation reservoir operation, was proposed in this paper. The model may be used to quantify the risks associated with annual repeatability and expected water shortages resulting from a specific reservoir release strategy. In addition, the model may be used to generate release strategies with the aim of ending the hydrological year at a certain reservoir storage level, thereby allowing a decision maker to review and compare tradeoff strategy choices.

The new model proposed in this paper forms part of a larger, ongoing research project on reservoir release strategy management at Stellenbosch University. Further work will include incorporating the model proposed here into a computerised decision support system and validating the decision support system by applying it to a special case study involving Keerom Dam.

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