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Reservoir operation and the frequency of decision making

STEPHEN J. L. MALLORY
Institute for Water Research, Rhodes University, 492 Dawn Road, Lynnwood, Pretoria, South Africa
stephen@waterresources.co.za

Abstract Restricting water use during times of drought is an accepted practice in many arid countries to ensure the sustainable use of reservoirs and large systems of interlinked reservoirs. The timing and magnitude of restrictions, referred to in this paper as an operating rule, has been investigated in terms of how often the decision is made as to whether or not to apply restrictions at any point in time. The current practice in South Africa is to make a decision once a year based on the state of storage in the reservoir or system of reservoirs together with stochastic projections of likely inflows over the next 5 to 10 years. The question that is explored in this paper is whether there is an advantage in making this decision more frequently. This analysis has been carried out by adapting an existing water resources model to be able to toggle between annual and monthly decisions. Several hypothetical systems were modelled using both annual and monthly decisions based on the state of storage of the system. The systems modelled varied from those with large carry-over periods, or long critical periods, to those with short critical periods. Multiple users with high and low risk profiles were included in the simulations. The outcome of these simulations in terms of the volume of water supplied to high and low risk users was recorded for each simulation. The conclusion reached is that there is a significant benefit to users from systems with short critical periods to make more frequent decisions on water restrictions rather than an annual decision. Based on this conclusion a recommendation is made about the appropriate frequency of decision making based on the type of system and the risk profile of the user.

Key words Reservoir Operation; assurance of supply; water restrictions; hedging

INTRODUCTION

Restricting water use during times of drought, also referred to as hedging, is an accepted practice in many arid countries to ensure the sustainable use of reservoirs and large systems of interlinked reservoirs. The reason for this is that in arid countries it is generally not economically viable to construct dams large enough to ensure a continuous unrestricted water supply. Apart from the unfavourable economics of water supply in arid countries, droughts can be of such a nature that it is not physically possible to supply an unrestricted supply. This is certainly the case in most of South Africa and hence water restrictions are an accepted tool to manage water resources in a sustainable manner.

Water resources modelling tools, sourced originally from Canada, were developed further in South Africa to manage and further develop the Vaal water system, a complex system of interlinked catchments which transfer water to South Africa's economic centre located in the Vaal River catchment. These modelling tools, referred to as the Water Resources Yield Model are described in various publications (Basson *et al.*, 1994; Department of Water Affairs and Forestry, 2007). A stochastic modelling approach was adopted at the time of development of these models with the aim of increasing the reliability of the bulk water supply systems by introducing worse sequences of droughts into the modelling process than have been observed. Due to the huge number of computations required to simulate multiple hydrological sequences, model runs in the 1980s when the model development was in progress were time consuming and it was probably for this reason that the models, once set up, were only used once a year to make a decision on whether or not to impose restrictions. Since the Vaal System has large storage relative to the natural runoff, and hence an unusually long critical period, an annual decision was and still is adequate.

More recently, South Africa's Department of Water Affairs have made a concerted effort to develop operating rules for small systems. This was done through a study referred as the "Stand Alone Dams" project (Mallory *et al.*, 2013). During the course of this study, it was noted that dams with small storage relative to their natural runoff had short critical periods, sometimes of less than a year. In these circumstances an annual decision on whether or not to impose restrictions is clearly inadequate and operating rules were developed which allowed operators to review the situation every month. The question then arose, when should a monthly rather than an annual decision be applied and what advantages are there, if any, of a monthly rather than annual decision. This question was investigated and is reported on in this paper.

METHOD

In order to compare monthly and annual decisions, an existing water resources model, the Water Resources Modelling Platform (Mallory *et al*., 2011) was adapted so that the modeller can toggle between a monthly or annual decision. Within this model, the decision on whether or not to impose restrictions is based on the state of storage in the dam which was determined through trial and error modelling, firstly using a single set of natural inflow time series and then refining the rule based on 100 stochastic natural inflow time series generated using an Autoregressive Moving Average Model (Salas & Pegram, 1978).

The intention was initially to compare the assurance of supply experienced by water users with different risk profiles when subjected to the alternative operating rules (monthly or annual). However, when comparing results it was realised that assurance of supply is not the only criteria for evaluating alternative operating rules. The length of time over which restrictions are imposed (average and maximum) are also important, as is the average volume of water supplied. Hence a more comprehensive set of evaluation criteria were developed.

Risk profiles, within the context of water resources modelling and planning, are defined here as the ability or willingness of a user to accept water restrictions during droughts. A risk profile has two parameters, the degree of restriction the user can accept and the frequency of the restrictions (also referred to as assurance of supply). Generally irrigators have a high risk profile in that they are prepared to accept larger restrictions more often than urban or industrial users. For this reason, industry and urban users are generally prepared to pay much more for their water than the agricultural sector.

While the term "assurance of supply" is in common use in Southern Africa a search for definitions of assurance of supply resulted in very few clear definitions. The clearest definition was that found in a report by consultants SWECO (SWECO International, 2009) which defines assurance of supply as "*the percentage of time steps with fully satisfied water demand over the total hydrological record*". Internationally it seems the preferred term to describe the risk of failure is "reliability" (Kjeldsen *et al*., 2004) where reliability is defined by Kjeldsen as:

$$Rel = 1 - \frac{\sum_{j=1}^{M} d(j)}{T} \qquad (1)$$

where $d(j)$ is the duration of the jth failure event, M is the number of failure events, and T is the total number of time intervals in the simulation. For all practical purposes, reliability is the same as assurance, the only difference being that assurance is expressed as a percentage.

The SWECO report did not indicate the length of time step used within their simulations but it is understood that SWECO used a monthly time step model on the project referred to in the referenced report. The models on the Vaal System referred to in the introduction (Department of Water Affairs and Forestry, 2007) do not directly define assurance of supply, but it is inferred in their definition of long term yield (Basson *et al*., 1994) that the time step used in their calculation of assurance is one year and not one month as defined by SWECO. The outcome for a water user varies greatly depending on the definition since a single failure within one month in every year would imply a 0% assurance (using a year as the time step) while using the SWECO definition this would be a 91.67% assurance (full supply in 11 out of 12 months). For the purposes of this paper the SWECO definition was adopted as being more realistic and in line with most practitioner's understanding of assurance of supply.

One of the hypotheses investigated in this study is whether the size of a reservoir relative to its inflow has a bearing on how it is operated in terms of restrictions. A range of dam full supply capacities, from 10% of the mean annual runoff (MAR) into the dam up to 200% were therefore modelled with both a high (irrigation) and low (urban) risk profile users. The risk profile was applied by applying restrictions on water use when the water level reaches a certain storage. The sooner restrictions are applied, the lower the assurance and *vice versa.* The restriction rules used in the simulations are shown in Tables 1 and 2. In this particular exercise the rule is applied to one reservoir only.

Table 1 Urban restriction rule (low risk profile).

Storage (% of full supply capacity)	Restriction applied
≥ 40	0%
20 to 40	10%
10 to 20	15%
≤ 10	20%

Table 2 Irrigation restriction rule (high risk profile).

Storage (% of full supply capacity)	Restriction applied
≥ 50	0%
30 to 50	20%
	40%
	60%

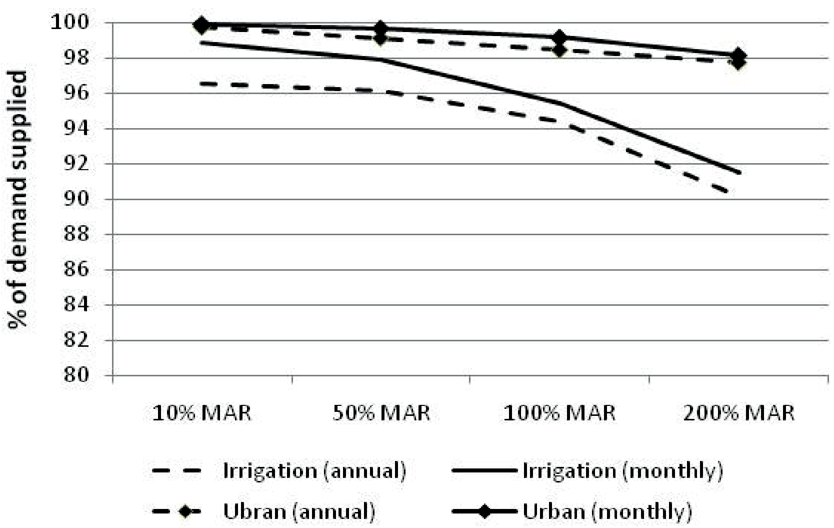

Fig. 1 The percentage of demand supplied to irrigators (high risk profile) and urban users (low risk profile) assuming monthly and annual decision making on whether or not to impose restrictions.

The demand placed on the dam in each analysis was 10% more than the safe yield of the dam. This was to ensure that restrictions were applied to both users (irrigation and urban) during the simulation.

RESULTS

As discussed in the previous section, there are several ways to compare reservoir operation, with some factors being more important to some users than others. The factors reported on in this paper are:

– Total volume of water supplied over the simulation period, expressed as a percentage of the water demand imposed by the user on the dam
– Assurance of supply
– Average duration of restriction
– Maximum duration of restriction

Figure 1 shows how the total volume of water supplied changes depending on whether the decision to restrict is made every month or only once a year.

Figure 2 shows how the assurance of supply changes depending on whether the decision to restrict is made every month or only once a year.

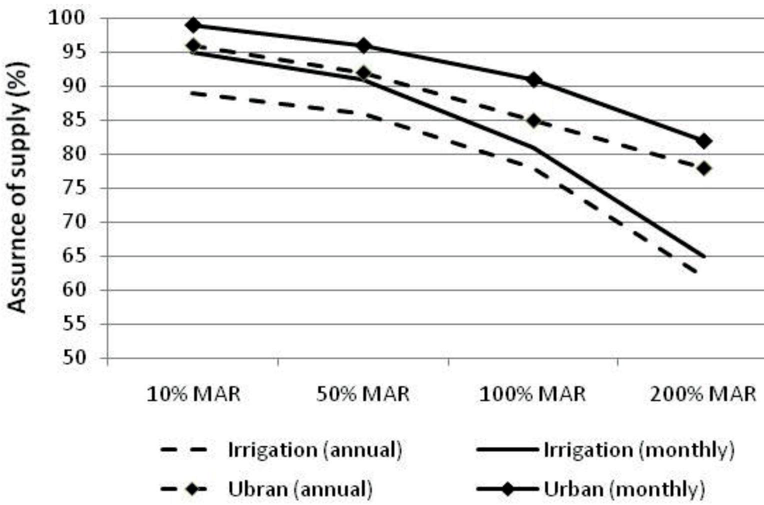

Fig. 2 The assurance of supply experienced by irrigators (high risk profile) and urban users (low risk profile) assuming monthly and annual decision making on whether or not to impose restrictions.

The maximum duration of a drought (or the period over which restrictions are imposed) could be important to some users. For an irrigator a period of harsh restrictions will definitely result in substantially reduced income and small-scale farmers with limited access to financing will not be able to tolerate restrictions for prolonged periods. This maximum duration was therefore also evaluated to see how this changed depending on annual or monthly decision making. See Fig. 3 (irrigation) and Fig. 4 (urban).

The average duration of restrictions was also evaluated. See Figs 5 and 6.

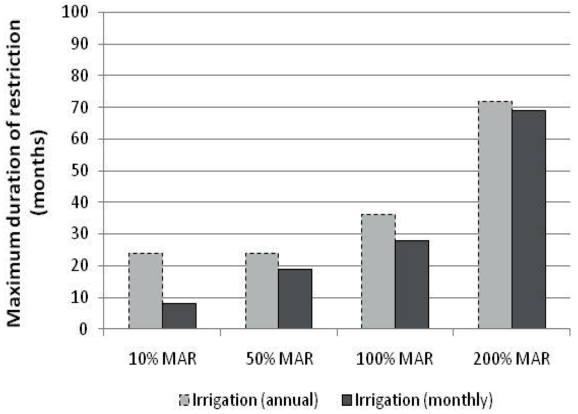

Fig. 3 The maximum duration of restrictions experienced by irrigators (high risk profile) assuming monthly and annual decision making on whether or not to impose restrictions.

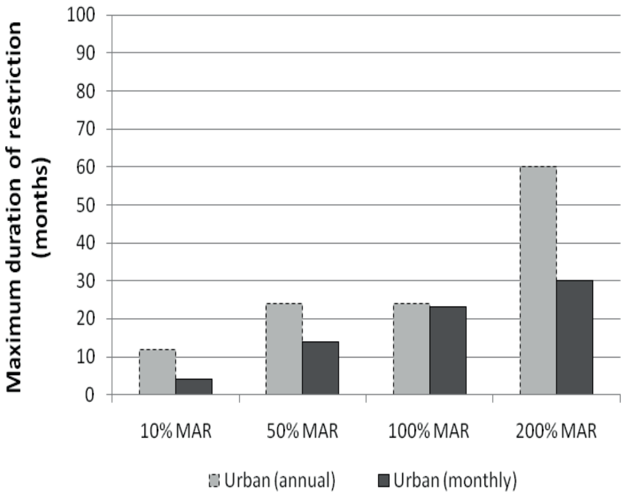

Fig. 4 The maximum duration of restrictions experienced by urban users (low risk profile) assuming monthly and annual decision making on whether or not to impose restrictions.

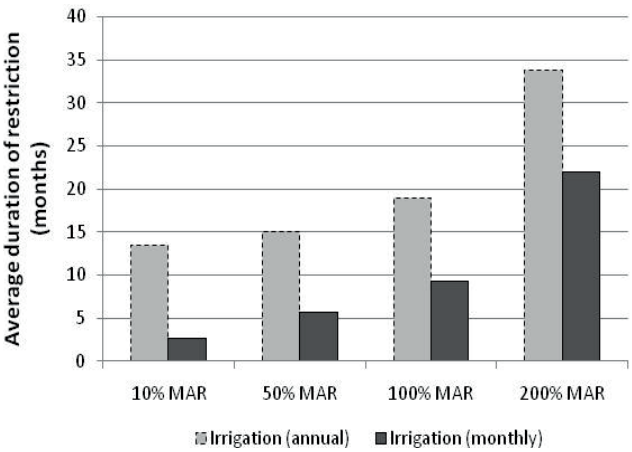

Fig. 5 The average duration of restrictions experienced by irrigators (high risk profile) depending on whether the decision to impose restrictions were made monthly or annually.

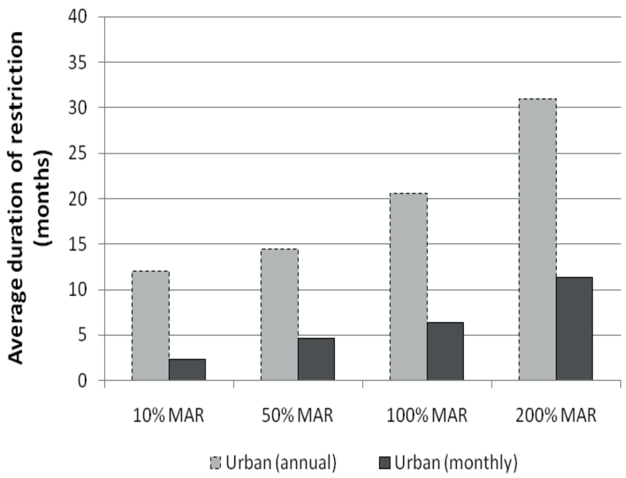

Fig. 6 The average duration of restrictions experienced by urban users (low risk profile) depending on whether the decision to impose restrictions were made monthly or annually.

DISCUSSION

It is clear from the analysis of different operating rules (monthly *versus* annual decision making), as shown in Figs 1–6, that there is a significant difference in how water will be supplied to users depending on how often decisions are made to apply restrictions. Intuitively it would be expected that assurance of supply would improve dramatically switching from annual to a monthly decision and yet the improvement, while significant, is small. The improvement is more noticeable the smaller the dam relative to the mean annual runoff (MAR) of the catchment. Similarly, while the volume of water supplied is larger when a monthly restriction rule is used rather than an annual rule, the increase in volume supplied is insignificant.

Of more significance is the impact that the frequency of decision frequency making has on the maximum duration of the drought period, as well as the average duration of the drought period. Both are significantly shorter if decisions are made every month than if they are made every year. Again, the benefit of the monthly decision regime is large to high risk users supplied out of small dams (relative to the catchment MAR). Time series of water supplied to high risk and low risk users further illustrate this point (see Fig. 7 (high risk profile) and Fig. 8 (low risk profile)).

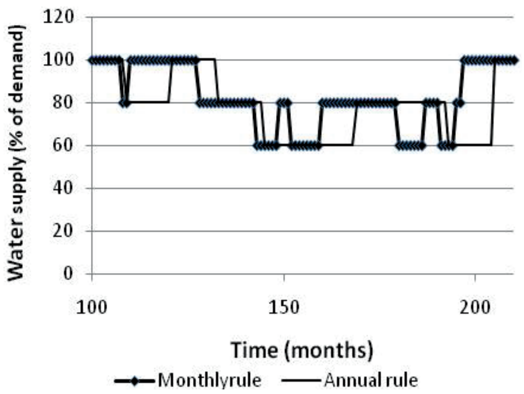

Fig. 7 Selected time series of water supply to irrigators with monthly and annual decision making.

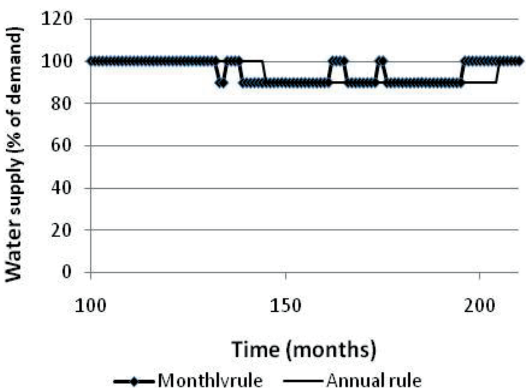

Fig. 8 Selected time series of water supply to urban users with monthly and annual decision making.

While the benefits of monthly rather than annual decision making have been clearly demonstrated in this paper, there are other factors that need to be taken into account when deciding on which operating rule to use. While the benefit to irrigators (and other high risk profile user), is the most significant, some irrigators still prefer making an annual decision. These irrigators are generally growing seasonal crops and there is a benefit for them to know how much water is to be allocated to them during the coming growing season. The area of crop planted will then be determined according to the available water. However, the same rationale does not apply to perennial crops. In the author's experience, some municipalities have requested an annual allocation in advance of the water year, as do some irrigators, their reasoning being that they can then budget better with the knowledge of how much water they are likely to sell during the year and plan ahead for restrictions if necessary. There is merit in these arguments and the recommendation is that water resources models should be sufficiently flexible to accommodate annual and monthly rules applied to different users within the same simulation.

The above analyses have been carried out using a historical record of 85 years. Hence the uncertainty of the annual inflow relative to the monthly inflow has not been considered. This could be done using stochastic models. The influence of climatic regions or climate change has also not been considered. So while the results of this comparative analysis are not surprising, there are clearly more aspects that need to be explored.

SUMMARY AND CONCLUSION

The impact of water supply on how frequently decisions on whether or not to impose water restrictions was investigated with the intention of demonstrating the advantage of a monthly decision rather than an annual decision. The conclusion reached was that high risk profile users supplied from small dams (relative the catchment MAR) will benefit the most from increased frequency of decision making. Nevertheless, the improvement in terms of assurance of supply and increased total volume of water supplied (on average over a long period) is significant, but not large. Of more significance is the reduced maximum and average duration of the restriction. This would have advantages to small-scale irrigators. The recommendation from this study is that irrigators supplied from small dams (relative to the MAR) should operate on a monthly restriction rule in order to maximise assurance of supply while minimising the duration of restrictions. Nevertheless, some irrigators, especially those growing seasonal crops, prefer an annual allocation and water resources planners should accommodate them in their modelling and planning. Water resource models should therefore be sufficiently flexible to accommodate annual and monthly rules applied to different users within the same simulation.

The results of this study could be considered to be obvious and trivial. Monthly data provides more information that annual data and hence improved operation should be obvious. Nevertheless, the practice of applying an annual operating rule is deeply entrenched in Southern Africa and the analysis presented here should provide a motivation to reconsider an annual decision. Also, the analysis raises questions as to the uncertainty relating to an annual *versus* monthly decision. It is suggested that these are issues that could be explored further by comparing annual stochastic models *versus* monthly stochastic models within the framework of annual and monthly decisions.

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