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Reservoir operating rules across a range of system complexities and degree of operator competencies

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Abstract South Africa, as with most developing countries, has historically focused its efforts on developing operating rules for reservoirs and systems of interlinked reservoirs on large schemes which support major economic zones. In order to achieve a more equitable approach to water resources management, South Africa embarked on a process to develop operating rules for the smaller reservoirs and systems supplying water to towns and rural areas. This process entailed developing operating rules for over 100 dams across the country. This paper presents some of the lessons learnt from this process. One of the main conclusions is that the operating rules need to be adapted to the level of sophistication that can be accommodated by the reservoir operators. In its simplest form the operating rule is a description of actions to be undertaken under various situations. At the other extreme operating rules consist of complex decision support systems which include stochastic simulation models which carry out simulations every month and advise users of the risk of entering a restriction zone in future so that informed decisions can be made. This could include advice on transfer of water from other sources, the conjunctive use of surface and groundwater, or using desalination plants during serious droughts. A range of example operating rules are presented which cover the scope of this project. The conclusion reached in this paper is that a systematic approach is required to identify the type of operating rules that are applicable in any given situation, and a possible systematic approach is presented.

Key words Reservoir Operation; water restrictions; decision support systems

INTRODUCTION

South Africa is a water scarce country with mean average rainfall of 450 mm/annum, well below the global mean of 860 mm/annum (Department of Water Affairs and Forestry, 2004). South Africa's water situation is exacerbated by the uneven distribution of rainfall, with high rainfall in the east (in excess of 1000 mm/year) in places, and <100 mm/annum in the west. However, the water requirements are not necessarily located where water is readily available since cities historically developed around mineral resources and ports and not where water was in abundance. As an example, in order to sustain the water supply to the Johannesburg/Pretoria metropolis (the economic hub of the country), it requires a complex system of transfers from catchments located in the eastern escarpment, and from Lesotho, a mountainous country contained within the borders of South Africa. It is complex systems such as this that resulted in the development of water resources modelling tools in South Africa which have been used extensively to develop operating rules for dams and systems of interlinked dams. These models are described in several publications (Basson *et al*., 1994; Department of Water Affairs, 2004).

While most of the water supply systems relating to large urban centres have operating rules, until recently the operation of water for smaller towns and villages was largely ignored. The reason for this is the smaller towns fall under the jurisdiction of local government and not central government, and local government mostly did not have the technical capability or the financial resources to undertake the necessary work to develop operating rules for their bulk water supply systems. Realising this short-coming, South Africa's Department of Water Affairs embarked on a national study, referred to as the "Stand Alone Dams" project to develop operating rules for all the smaller dams or systems. Development of these operating rules also needs to be viewed in the context of increasing water demands associated with increased service delivery and the legal requirement to meet the ecological reserve. The prospect of climate change is also a motivating factor for the development of operating rules. Although there is no conclusive evidence at present of climate change altering the rainfall or the runoff within South Africa, predictions are, however, that rainfall patterns will change and water resource planners need to be in a position to respond appropriately to these changes.

This paper discusses the difficulty in developing operating rules across the wide range of system complexity encountered during the course of the study as well as the range of operator competency. A range of operating rules, from very simplistic generic rules to complex real-time systems, recommended to deal with this problem and a method to classify each dam (or system of dams) has been developed as a proposed solution to this problem.

THE NEED FOR OPERATING RULES

In developing countries, such as South Africa, there is political pressure to improve water services and large budgets and human resources are allocated to this task. However, the design of water schemes seldom considers how the water supply system is to be operated once complete. As part of the solution towards improving water services delivery, the so-called Stand Alone Dam project was initiated. This study covers the whole of South Africa with the objective of developing operating rules for all the small dams supplying towns and rural communities. The dams were prioritised in terms of the importance of the water supply and the perceived risk of failure. To date operating rules for more than 100 dams have been developed and documented. The Stand Alone Dam project is therefore retro-actively developing operating rules for the many dams and schemes that were built without the development of suitable operating rules.

COMPLEXITY OF OPERATING RULES AND OPERATOR COMPETENCIES

During the course of the Stand Alone Dam study, one of the more challenging and unexpected findings was the lack of understanding of water resources systems within local authorities, as well as the lack of basic measuring devices which would enable operators to take timely decisions, or at least alert the appropriate authorities of the impending problem. The operating rules generally used for complex systems were found to be, at best inappropriate and at worst non-implementable due to the lack of even the most basic measurements required for water resources management.

In order to develop appropriate operating rules that have at least some chance of successful implementation, it was therefore necessary to understand the range of complexities and operator competencies that are likely to be encountered. At the one extreme, dams encountered during the course of the Stand Alone Dams project did not even have gauge plates and the storage capacity of the dams was uncertain. Even though the catchments of the dams were easily delineated and inflow estimated using national hydrological datasets (Middleton & Bailey, 2007), without knowledge of the dam’s storage capacity it is not even possible to determine the safe yield of the dam (or system of dams). Hence the sustainability of such schemes is unknown or at best very uncertain. At the other extreme, systems are supplying multiple users at different levels of assurance from multiple sources. These systems often have legislated ecological flow requirements which require real-time operation to implement fully. Users such as navigation and flood control were not encountered during the study but it is acknowledged that these are valid users in some systems which would add further complexity to the system.

Multiple sources of water introduces a high level of complexity in most bulk water supply systems. The introduction of sources such as groundwater, desalination and water re-use adds to this complexity. Under this scenario, the target draft *versus* assurance characteristics of each source needs be evaluated and then an optimal rule developed as to when which source, or combination of sources, should be used or restricted.

The issue of cost of operation was also encountered during the course of the study. Some local authorities, in the absence of a detailed understanding of sustainable water resources management, favour operating the system to minimise the cost. If allowed, this could result in the failure of the system and hence failure of the overall objective of an operating rule, which is the sustainable management of the water resources.

While technical solutions can always be found, the bigger challenge in developing countries is finding appropriately skilled people to implement the proposed solution. Of the 40 dams or systems analysed by the authors, not one was operated by a fully qualified or experienced water resources practitioner. Nevertheless, a few of the operators, through years of experience, have developed an intrinsic feel for how a system should be operated, and in these cases the operators had a clear and rational operating rule, even if this was not well documented and/or scientifically proven at the time. Where identified, rules applied successfully by experienced operators were generally retained with minor modifications and improvements. At the other extreme, operators in deeply rural areas have no technical skills at all and simply open and close valves to supply water on demand. At the onset of the study, several dams were identified as being of very high priority because they were reported as being empty. Invariably it was found that these dams were empty due to leaking outlet works or valves inadvertently being left open. In one case the water level gauge plate had fallen off the outlet works and the null reading was accepted as zero or empty.

In order to be successful, operating rules should address all the above complexity and operator issues. Hence a system to evaluate the level of complexity and operator skill has been developed and is described in this paper.

POSSIBLE RANGE OF OPERATING RULES

In order to address the problem of operator competency, or the lack thereof, it is suggested that operating rules need to be tailored to the level of competency of the operator and the amount of information available in real-time from the dam or system. The following approaches are suggested:

No information available

During the South African Stand Alone Dams study, several dams investigated had no gauge plates and no effort was being made to monitor the storage in the dam or the water use from the dam. Under these circumstances, it is pointless developing operating rules, even at the most fundamental level, and efforts should rather be channelled towards installing gauge plates, surveying the reservoir basin and training dam operators. Only then can operating rules be developed.

Dam operator with no formal training

In developing countries, dam operators often have no training in maths and science, and have difficulty understanding graphs and would certainly not be able to use even rudimentary software such as Excel. In these cases, it is suggested that operating rules need to be expressed in purely descriptive terms, for example. “when the water level in the dam drops below 10 m, reduce the supply to users to 1 Ml/day”.

Dam operator with graphical capability

Graphical tools such as Excel are a relatively simple way to visualise how a dam is operating and provides insights into what might happen in the future simply by keeping a record of how the dam operated in the past. Coupled with this, the water levels at which restrictions should be imposed on various users can be shown graphically. An example of this simple form of operating rules is shown in Fig. 1.

An operating rule, such as that shown in Fig. 1, can be developed with a water resources model by trial and error modelling. In this case the Water Resources Modelling Platform (Mallory *et al.*, 2011) was used. This model allows the dam to be divided into a number of storage zones. Restrictions are incrementally imposed or lifted as the storage progresses through the storage zones. The operator records the storage of the dam on the spreadsheet and then makes a decision whether or not to impose restrictions. This was developed and the simplest form of operating rule for operators within minimal technical skills.

The operating rules can be developed using single time series of estimated inflows obtained from national hydrological datasets (Middleton & Bailey, 2007) over a long period of time, but should preferably be developed using stochastic hydrology so as to allow for the worst case

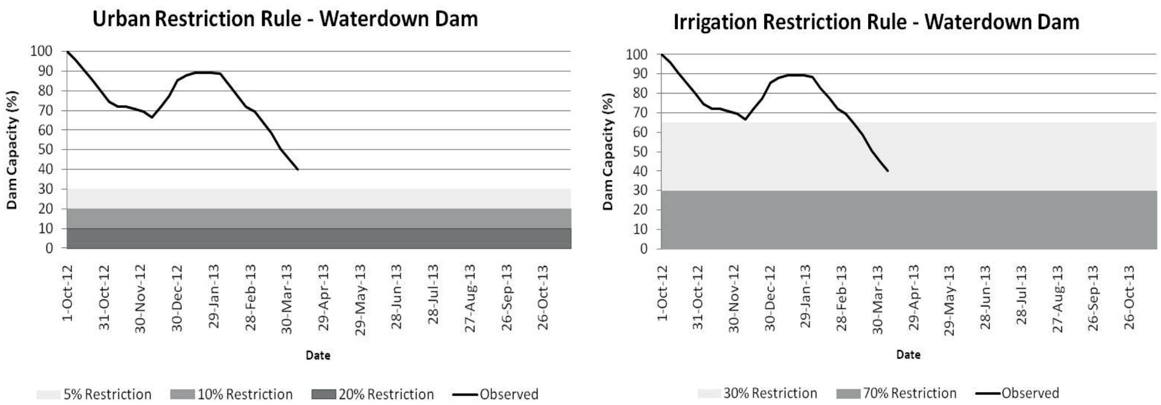

Fig. 1 Typical operating rule for dam operators with limited training.

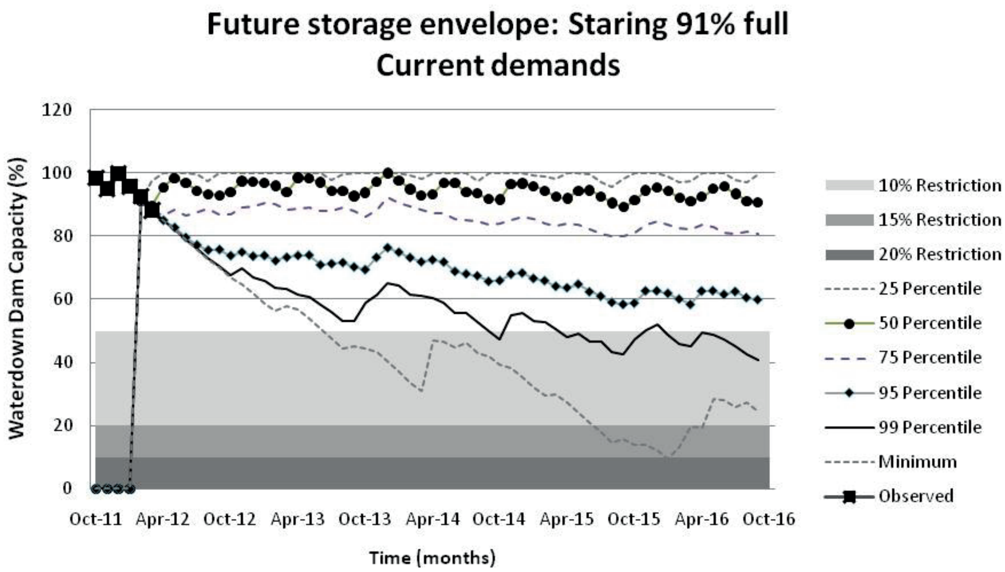

Fig. 2 Operating rule using stochastic analysis.

drought sequence. The operating rules shown in Fig. 1 were developed using 500 stochastic natural flow time series.

Complex systems requiring frequent reassessment

The operating rule shown in Fig. 1 is only applicable while there are no major changes in the system, such as new water allocations, unexpected water losses, etc. Systems which are in a continuous state of flux and/or are of high economic or social value require more diligent monitoring. In these systems, an envelope of possible future storages is generated using 500 stochastic inflow time series. Combining this with past observed storage helps keep track of actual *versus* modelled system performance. If the observed storage falls outside of the possible range or envelope of storages, then the reason for this must be investigated and resolved. This would typically be due to a user using more than assumed in the model. This might then require a change in the operating policy in terms of water restrictions.

The recommendation for complex and critical systems is to carry out a model simulation every month to ensure a speedy reaction to deviations from the expected performance and to provide adequate warning of impending droughts and possible water restrictions. This allows local authorities to plan ahead for such eventualities.

This type of operating rule requires a high degree of expertise to implement successfully and is generally considered to be the responsibility of central government since local authorities do not have this level of expertise. Nevertheless, training of suitably qualified individuals within local authorities is an option that can be explored.

CHOOSING AN APPROPRIATE LEVEL OF OPERATING RULE

Deciding on the level of complexity of the operating rule to be developed based purely on technical considerations will often result in the failure of the rules to be correctly implemented. This is due to the limited skill and lack of training of the operator. While training and/or recruitment of suitable operators must always be recommended where skills are lacking, it is suggested that developing rules that are appropriate to the skills of existing operators is the first step towards successful implementation of an operating rule. Improvements can always be made over time as the skill and experience of the operator improve over time. The importance of the water supply and the willingness of water users to pay for water will help decision makers to prioritise training programmers to elevate initial simple operating rules to more robust and scientifically acceptable rules.

In order to assist those responsible for developing operating rules to target an appropriate level of technology, a decision matrix has been developed, as shown in Table 1.

Table 1 Selecting an appropriate rule and action for improvement.

System complexity			
High	Rule: Descriptive	Rule: Graphical	Rule: Real-time
	Action: Recruit suitable operator and update to real-time operation	Action: Recruit suitable operator and update to real-time operation	Action: Monitor and update rule when required
Medium	Rule: Descriptive	Rule: Graphical	Rule: Graphical
	Action: Provide in-service training and update to graphical rule	Action: Monitor and update rule when required	Action: Monitor and update rule when required
Low	Rule: Descriptive	Rule: Descriptive	Rule: Descriptive
	Action: Monitor	Action: Monitor	Action: Monitor
	Operator competency		
	Low	Medium	High

System complexity is not rigidly defined, but the following guidelines can be used to assist decision makers as to the type of operating rule to be applied:

Low system complexity: Single dam, single user
Medium complexity: Multiple dams (not interconnected), multiple users
High complexity: Multiple dams and/or alternative sources of water; interconnected systems; multiple users.

DEALING WITH A LACK OF DATA

Developing an operating rule if the full supply capacity of the dam is not known and the dam is not equipped with a water level gauge is not possible. The obvious solution is to determine the full supply capacity and install a gauge, but for various reasons this can take some time in developing countries. Even once this is done, operators do not necessarily share their observed water levels with central government and hence monitoring is at best difficult, but in some cases impossible. An alternative is the use of monthly (or possibly weekly) satellite images from which the surface area of dams can be measured. From this, the volume of the dam can be estimated. While not as accurate as a physical survey, it will at least give an indication of the state of storage of dams which are currently unknown. This will allow central government to intervene before the storage drops to critical levels and the water supply situation becomes a crisis, as has happened frequently in the past.

CONCLUSIONS

Developing operating rules for dams is technically not difficult, but in developing countries the challenge is to find competent dam operators who understand the operating rules and will apply them diligently. The recommendation made in this paper is that the complexity of the operating rules must compliment the level of competency of the operator if it is to be successful. It must be stressed, however, that this is only an initial starting point and that operators must be trained up to the level of competency required of the operating rule, however complex this may be. Through training and/or recruitment, more advanced operating rules can then be developed to meet the complexity of the system. The importance of the water supply scheme is also a factor to take into consideration and it is suggested that the importance should be used to prioritise training programmes so that more detailed and robust operating rules can be implemented over time to improve the reliability of supply to important systems.

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