Development of Optimised Conjunctive Control Rules for a System of Water Supply Sources

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Abstract

Due to the large and often competing demands for water and increasing importance of sustainability criteria, water resource managers have begun to examine closely ways in which the operation of existing and planned reservoirs could be optimised. Guidelines have been devised on the operation of multi-purpose, multiple reservoir water systems, but there remains no methodology generally accepted by water resource managers for deriving multiple-reservoir operating policies.

This paper proposes a new approach to the optimisation of the operation of multiple reservoir systems. The revised methodology develops the concept of an extended drought period to evaluate additional emergency storage reserve extending the reliability of the system. The operation of the Roadford Reservoir System, South West England, consisting of nine reservoirs was studied. Through simulation analysis, the control rules for each reservoir were revised based on the concept of low volumes of demand deficit. The report highlights the superior results compared with the current operating control rules.

Key words: Conjunctive-use; control rules; multiple-reservoir systems; water supply; optimisation; Roadford reservoir.

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Introduction

The operation of most multiple-reservoir systems demonstrates that there are sometimes conflicting and complementary multiple purposes served by the water stored in and released from reservoirs. Control curves have been used in the United Kingdom for more than 50 years to reduce operating costs by controlling the overdrawing and pumped refill of reservoirs.(1) However, for over 25 years some water companies within the UK have been integrating their sources into resource zones so there has been a need to produce conjunctive control rules applying to a whole system.(2)

The conjunctive use of a multiple-reservoir system was described by Walsh(3) as "the joint use of two or more water resources according to a planned rule, leading to a cheaper supply than that gained by their independent use". When using sources conjunctively, multireservoir operating policies are usually defined by 'rule curves' that specify either desired individual reservoir (target) storage volumes or desired (target) releases based on the time of year and the existing total storage volume in all reservoirs.(4) Reservoirs can have multiple rule curves made up of winter refill curves and summer drawdown curves (see Fig. 1). Rule curves that regulate the drawdown of a reservoir are referred to as control rules within this paper. The purpose of control rules as operating policy guides is to provide criteria for distribution deviations from target conditions so as to minimise variance from the desired conditions and prevent infringements of the mandatory regulations.

The underlying objective of this research was to develop an improved methodology for identifying optimal control rules that ensure the required level of service and allow the allocation of excess water for large conjunctive use systems. Through refinement of the existing operational rules, developed by the Environment Agency (EA)[5], an optimum balance between environmental impact/benefit, sustainable resources, drought reliable yield and operating costs can be achieved.

The Centre for Water Systems (CWS) applied revisions to the current methodologies adopted by the EA. Simulating Roadford Reservoir System in the Water Resources Model (WRM) provided demand deficit data from which comparisons were made with results gained when the original control rules were implemented.

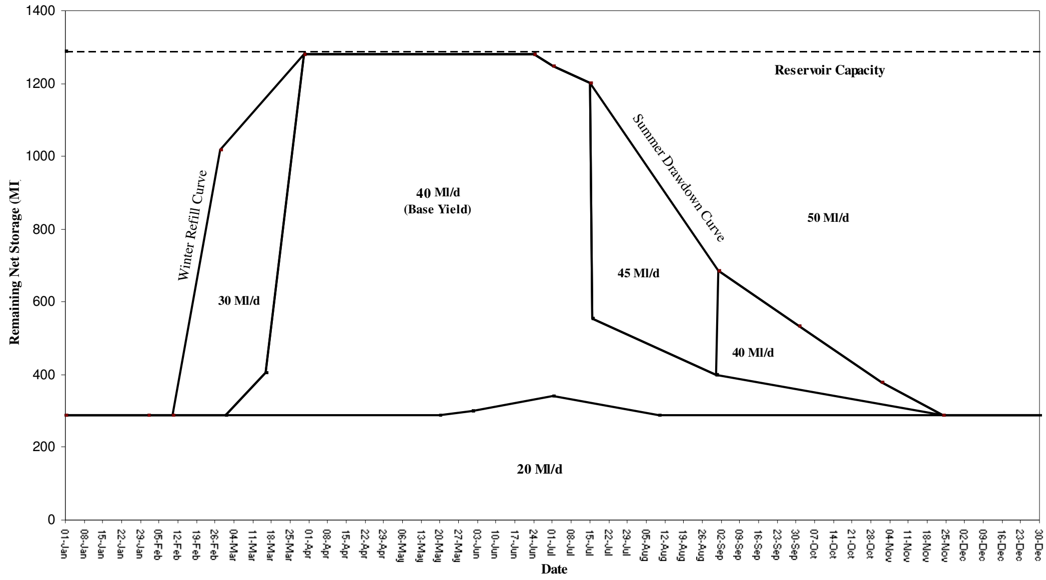

Fig. 1. Example of a control rules graph for a typical reservoir

Methodology

Calculations for the revised control rule ordinates were divided into two separate stages. Firstly the inflows, which might occur during the design drought, were calculated from statistical analysis of the inflow data. Secondly these 'design drought inflows' were converted to values of storage required by the process of balancing inflow and outflow.

Table 1 outlines the design criteria of the Centre for Water Systems (CWS) and the EA control rule methodologies.

Table 1. Characteristics of each control rule methodology

Methodology	**Summer Drawdown**	**Winter Refill**	**Emergency Storage**
ENVIRONMENT AGENCY	Worst Historic Inflow	99% Refill Chance	-
CWS 1	Worst Historic Inflow	99% Refill Chance	30-day
CWS 2	1 % Inflow	99% Refill Chance	Extended Emergency Storage
CWS 3	2% Inflow	98% Refill Chance	Extended Emergency Storage

Derivation of Design Drought Inflows

The development of a methodology for identifying optimal control rules for Roadford Reservoir System was based on average daily records (m^3/s) of the estimated flow from January 1st 1880 – December 31st 1995, from 17 sources, this data was supplied by the EA, South West Region. The monthly flow records pre-1957 were synthetically generated, based on rainfall-runoff modelling. These have been used with caution within this research.

Worst Historic Inflows

For the purpose of comparison between methods to determine 'design drought inflows', several techniques were chosen to calculate inflow. The first approach (CWS 1) used to establish the design drought inflows was based on the technique used by Walsh,[(3)] but in place of calculating the expected inflows at design probability levels, the worst historic inflows were chosen for each sequence.

Secondly, an iterative regressive algorithm for varying time spans, was developed to determine the lowest historic 'n' value for each of the twelve calendar months. The values of ‘n’ from one to 24 were used as they are representative of a ‘design drought’ that could extend over two summers.

Probability Distribution

The second technique used to determine a sequence of ‘design drought inflows’ was developed using the Log-Pearson Type III distribution(6) (CWS 2 & 3). Previous research of probability distributions on similar rivers,(7,8) concluded that the Log-Pearson Type III method best fits a theoretical distribution to a set of data from European rivers, which are characterised by high flows in the winter and low flows in the summer.

For each of the 288 sets of monthly inflow data, the n-month inflow (MI) corresponding to any selected per cent probability was determined. This was attained by fitting a frequency distribution to each of the data sets using the Log Pearson Type III distribution. This allowed the calculation of expected inflows at design probability levels of 1 and 2 percent. The calculation of the expected 2 per cent net inflow allows a 98 per cent chance that the reservoir will refill (an inflow equal to or less than this level is unlikely to occur, more than once in 50 years on average).

Drawdown Curves

The derivation of the CWS drawdown control curve ordinates was based on Lambert's[(5)] component-based method. Calculating the storage required at the beginning of each calendar month, derived the drawdown curves for each reservoir within the Roadford System. This storage level represents the minimum amount of water that must be stored in the reservoir in order to ensure that it can continue to provide a reliable supply to satisfy the net demands until the assumed drought end date. The calculations for all CWS scenarios were based on a typical dry years demand, 1995's demand data were chosen to be representative, as this shows the most recent pattern of the system under stress.

Drought End Date

When deriving operational control rules it was important to assess the reliability of the storage of the reservoir. The question most often asked during 'drawdown' periods relates to whether the resources can be made to last until the drought ends. Thus the judgement of the drought 'end-date' is important to avoid failure of water supply which is not a permissible option in the U.K. The current methodology used to derive the maximum drought sequence is calculated using the latest known summer drought end-date from hydrometric records.[(5)] However, due to the relatively short periods of flow records in this country a more practical approach was needed to decide on some statistics to describe a drought event. To create a factor of safety the maximum drought sequence was extended. Key intense drought sequences like 1976 and 1984, have a drought end-date of September, whereas other significant dry sequences like 1959, 1978 and 1989 were not as serious for most resource systems but had an end-date much later like October or November. The end-date will depend on the type of source. Generally a reservoir augmentation scheme with the abstraction point a long way downstream with a 'large' catchment will have an earlier end-date than a direct supply reservoir with a relatively small catchment, due to large volumes of rainfall reaching the augmented reservoir rapidly after a significant rainfall event.

Emergency Storage

To counter the uncertainty regarding how resilient a resource system is to droughts, based on analysis of historic sequences, an emergency storage value was added to the storage requirement at the end of a minimum drought sequence. At the British Hydrological seminar on Surface Water Aspects of the Department of the Environment Yield Review,[(9)] the point was illustrated that deployable resource calculations are highly sensitive to the emergency storage assumptions. For example, a reduction from the 30-day to 20-day emergency storage at Ennerdale (North West Water), would increase deployable yield by 25%. As sources become more integrated there is less risk in reducing the emergency storage at each. Therefore, two different methods of calculating the emergency storage have been examined:

i. 30-Day Emergency Storage (used in conjunction with CWS 1)

ii. Extending the 30-Day Storage (used in conjunction with CWS 2 and 3)

Worst Historic Inflow

In SWW's review of deployable resources,[(10)] the emergency storage of the reservoirs in the Roadford Reservoir System was based on 30 days of average demand (including compensation flow) minus typical average inflows during this period.[(10)] To create control rules incorporating this value, the emergency storage concept was developed, using assumptions as to how the values of typical inflow and average demand were calculated.

To assess the influence of the CWS methodologies the same inflow and demand data were used in the WRM. To determine the emergency storage, monthly inflow data between 1957-1995 for the Roadford Reservoir System was used for each reservoir. Although these sequences were of only 38 years duration, they included various severe droughts; 1959, 1975-6, 1978, 1984, 1989, 1990 and 1995, and were therefore considered suitable for the purposes of determining the level of emergency storage. To represent the typical inflow for each reservoir at the end of the summer period the average daily inflow of the worst historic extended summer drought (between April – October 1976) was calculated. This level was chosen as representative of typical inflow at the end of a summer when entering the autumn drawdown period.

The average demand used to calculate the emergency storage was determined using the base yield (see Fig. 1) of each reservoir. The base yield was selected as representative of the level of demand at the end of a summer (September - October) when demand has peaked and is falling.

Theoretical Droughts

The alternative method of calculating emergency storage was based on the number of days between the end of the worst historic summer drought and the end of the worst historic autumn drought, which then gave an Extended Emergency Storage (EES) of over 30 days for all reservoirs. For each reservoir, within the Roadford Reservoir System, the worst summer drought ends in 1976 and the worst autumn drought ends in 1978.

The drawdown of a reservoir was calculated using a design inflow probability, then an emergency storage value, calculated using the EES period, was added onto the refill value for the 1st of April. This raises the control rules (Fig 2). The EES values have been used with caution within this research as they were calculated using reservoir inflow sequences from groups of stations. Reference should be made to the original gauging stations to validate the emergency storage totals.

The effect of creating an emergency storage reserve for Avon Reservoir when adopting the control rule ordinates using the 2 per cent design inflow and EES, are highlighted in Fig. 2.

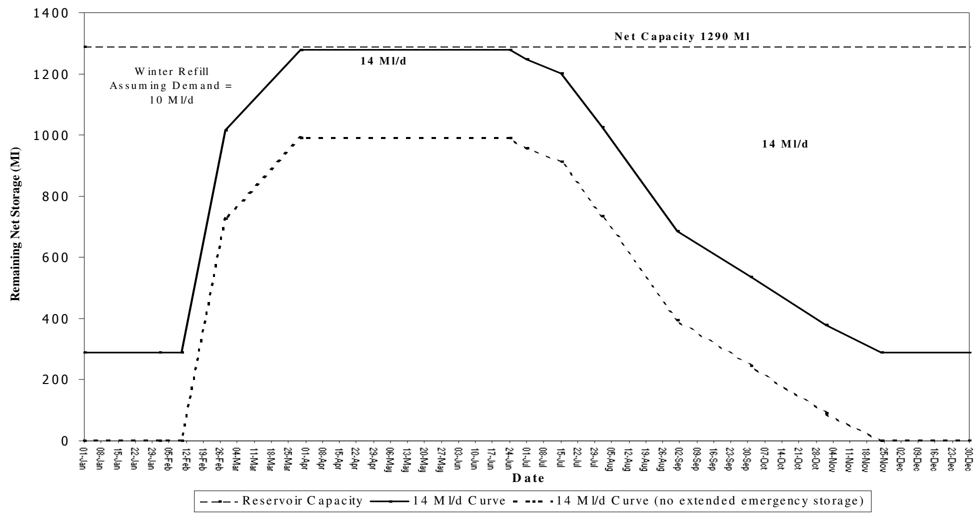

Fig. 2 Control Rule for Avon Reservoir Before and After Extended Emergency Storage is Applied, Designed Using 2% Inflow (CWS 3)

CWS Refill Curves

The derivation of the CWS winter refill curves (October – April) was based on Lambert's[5] component-based method. Calculating the storage required at the beginning of each calendar month derived the refill curves for each reservoir within the Roadford Reservoir System. This storage level represents the minimum amount of water that must be stored in the reservoir in order to ensure that it can continue to provide a reliable supply to satisfy the net demands at the beginning of the summer period (1st April).

The calculations for all CWS scenarios were based on a typical dry years demand, 1995's demand data was chosen as representative, as this shows a typical pattern of a system under stress. The refill curves required probability analysis of seasonal inflow data (October-March) to derive cumulative inflows, which are incorporated with basic demands and storage data.

Discussion

Simulation of System Operation

The WRM Version 4.20[11], provided by the Environment Agency South West Region, was the primary tool allowing comparison and evaluation of the results derived from the behaviour of the system when different control rules were applied. The WRM model is a representation of The Roadford Reservoir System used to predict the behaviour of the network under a given set of conditions.

Using the WRM it was possible to complete simulation runs for the control curves developed by the EA[5] and CWS (see Table 1). All the simulation runs were started on the first day of the historic data set, January 1st 1880 and ended on the last day December 31st 1995.

The results obtained from the WRM were on a daily basis and these were converted into monthly and annual values of demand and supply. This allowed the mid-month failures in the system to be highlighted, referred to as demand deficits within this paper.

Annual Demand Deficit

Simulation results from the three CWS control rule methodologies being entered into the WRM indicate significant demand deficits for all three methodologies in the dry years of 1887, 1921 and 1976 (Fig. 3). All three of the CWS methodologies cause significantly less demand deficit than the current operating rules employed by the Environment Agency.[(12)]

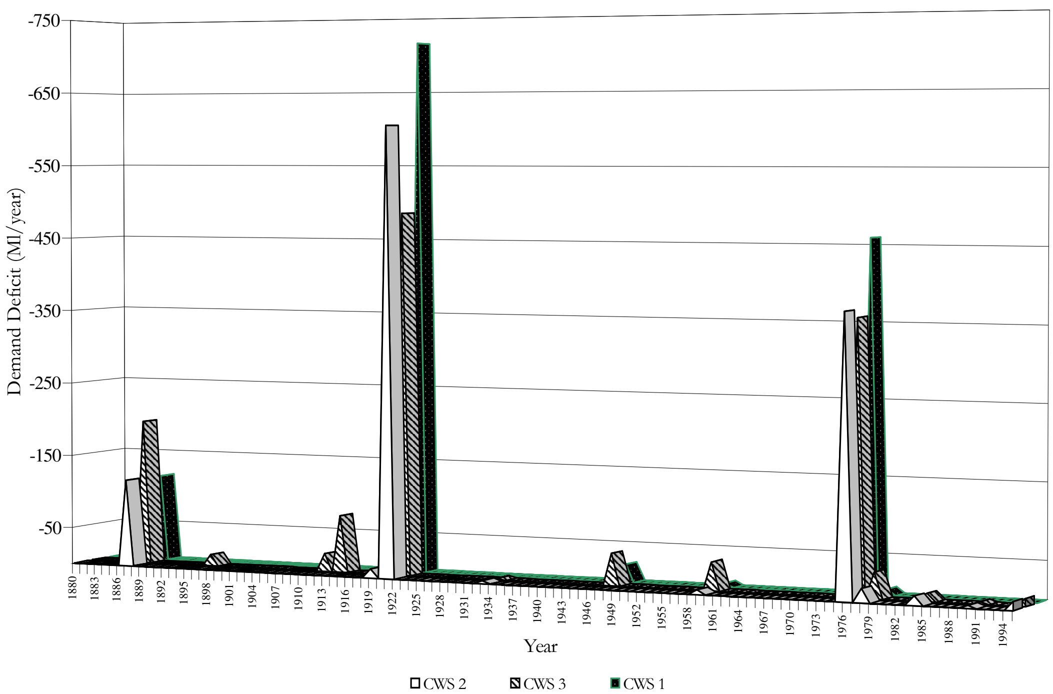

Fig. 3. Annual Public Water Demand Deficit for Roadford Reservoir System When Employing the CWS Control Rules

For the purpose of results comparison, the methodology that derived the control rules using the 1% design inflow, with the extended emergency storage (CWS 2), will be compared with the existing control rule methodology adopted by the EA, as this caused the least annual public water demand deficit over the 116 historic data set.

Fig. 4. illustrates the public water demand deficits when control rules developed using the CWS 2 methodology were simulated and compared with the rules designed using the methodology developed by the EA. In the driest years on record, 1921 and 1976, the CWS 2 rules caused one fifth of the public water demand deficit compared with when the EA control rules were applied.

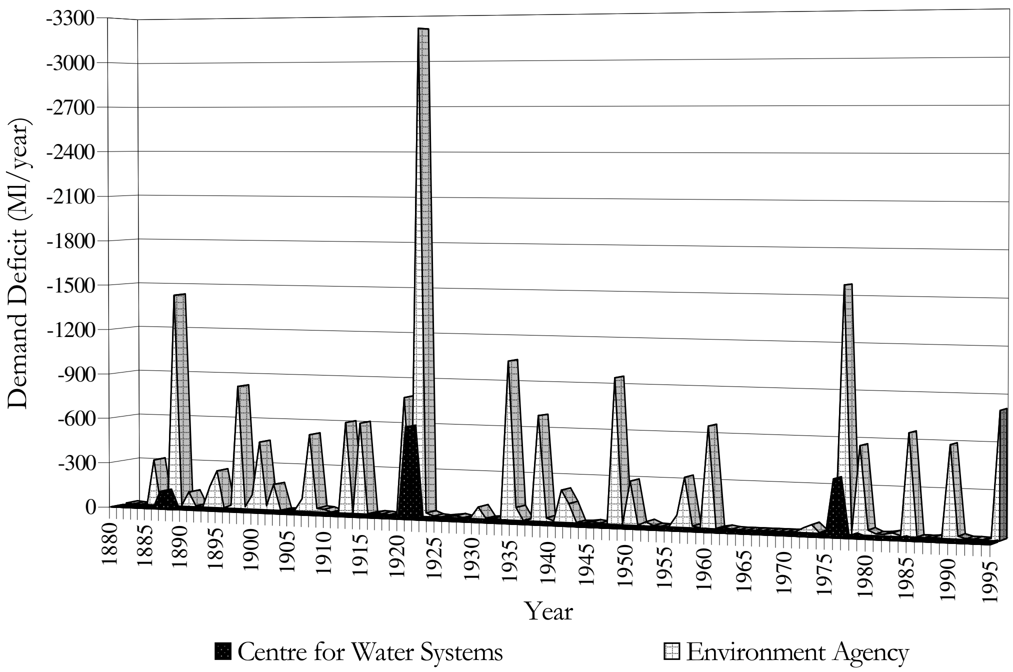

Fig. 4. Comparison of public water demand deficit when the CWS 2 methodology for control rule derivation is applied

By implementing the complete set of control rules designed using the CWS 2 methodology, the average yearly public water demand deficit for the Roadford Reservoir System over the 116 historic data set was reduced to 10 Ml. This is an average saving of 154 Ml per year compared with when the original EA control rules were implemented.

When the CWS 2 methodology is implemented nine of the sixteen demand centres experience no public water demand deficit over the 116 year historical data set. Further research is required to ensure each demand centre has an equal probability of public water demand deficit.

Conclusions

1. A new operating procedure for the Roadford Reservoir System has been developed. The recommended control rules were developed through detailed simulation of the daily operation of the Roadford System, using 116 years of historical data. Rule curves for all the reservoirs in the system were developed as guidance to ensure operators achieve supply targets to the maximum possible extent.

2. Data availability and the accuracy of the data generation method introduced problems concerning the replication of current methods of control rule design. Despite the data shortcomings, the recommended rule curve methodology discussed within this paper was designed to negate any effects on the day to day operation of Roadford Reservoir System.

3. Further research is required to distribute the deficit over the resource system to ensure an equal probability of deficit for each demand.

References

(1) PEARSON, D. & WALSH, P. D. The Derivation and Use of Control Curves for the Regional Allocation of Water Resources. *Optimal Allocation Of Water Resources,* (Proceedings Of The Exeter Symposium), 1982, Iahs Publ. No. 135.

(2) WALKER, S., & WYATT, T. The Development and Use of Medium Term Policies for Operation of A Major Regional Water Resource System. In *Proc. British Hydrological Society National Symposium.*, Sheffield, 1989, 4.47.

(3) WALSH, P. D. Designing Control Rules for the Conjunctive Use of Impounding Reservoirs. *J. Instn. Wat. Eng.,* 1971, **25**, (7), 371.

(4) OLIVIERA, R. & LOUCKS, D. P. Operating Rules for Multireservoir Systems. *War. Resources Res., 1997,* **33**, (4), 839.

(5) LAMBERT, A. An Introduction to Operational Control Rules using the 10-Component Method. *British Hydrological Society Occasional Paper No. 1*, 1988.

(6) KITE, G.W. *Frequency and Risk Analysis in Hydrology*. Water Resources Publications, USA, 1977.

(7) BENSON, M. A. 'Uniform Flood Frequency Estimating Methods for Federal Agencies'. *War. Resource. Res.,* 1968, **4***,* (5), 891.

(8) HAMLIN, M. J, & KOTTEGODA, N. T. Extending the Record on the Teme. *Journal Of Hydrology,* 1971*,* **12**, 100.

(9) BRITISH HYDROLOGICAL SOCIETY "Surface Water Aspects of the Recent DOE Yield Review". *Circulation,* 1998, **58**, June, 3.

(10) SOUTH WEST WATER SERVICES LTD "Agenda For Action" - Reassessment Of Water Company Yields. *Water Resources Group, South West Water, Exeter UK.* Volume 1. *November 1997.*

(11) ENVIRONMENT AGENCY- SOUTH WEST REGION. *Water Resources Model-User guide, Version 4.20,* 1998.

(12) SOUTH WEST WATER SERVICES LTD & ENVIRONMENT AGENCY *Roadford & Burrator Reservoirs – Operating Manual, Version 5*, 1997.