A SYSTEMS APPROACH TO WATER QUALITY MANAGEMENT DURING DROUGHT PERIODS IN THE CUMBERLAND RIVER BASIN

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INTRODUCTION

Operating complex water resource systems like interdependent multi-objective hydropower reservoirs to satisfy competing objectives is difficult. Most reservoirs are operated according to a guide curve which provides monthly headwater targets that meet reservoir and basin objectives under normal conditions. Guide curves, however, lack the sophistication to vary the headwater targets based upon changing conditions and priorities. Extreme conditions such as a drought exacerbate the problem, especially when combined with natural reservoir stratification and resulting water quality implications. This paper presents a method to determine alternative operating strategies under stratification and drought conditions. The Cumberland River basin in northern Tennessee and southern Kentucky is used as an example.

BASIN DESCRIPTION

The water resources of the Cumberland River basin (Figure 1) are well developed with most of the basin controlled by eight major hydropower dams. The river is an important economic resource for the region with four run-of-river reservoirs (Barkley, Cheatham, Old Hickory, and Cordell Hull) along the main stem allowing navigation through the lower 381 miles of the river. All four of these projects produce hydropower but have limited storage. They operate primarily to stabilize water levels for year-round navigation. Practically all inflows to these navigation pools are releases from upstream projects. Under non-flood conditions, the daily discharge from these run-of-river impoundments is generally quite similar to the inflow. The remaining four reservoirs are large storage projects with three (J. Percy Priest, Center Hill, and Dale Hollow) on major tributaries and one (Wolf Creek) above the navigable portion of the Cumberland. These storage projects function to retain and release water along a more beneficial schedule. They operate primarily to meet peak hydropower demands except during flood periods. As a result, operating characteristics of these projects include sporadic releases timed to coincide with peak power demands and widely varying headwater elevations.

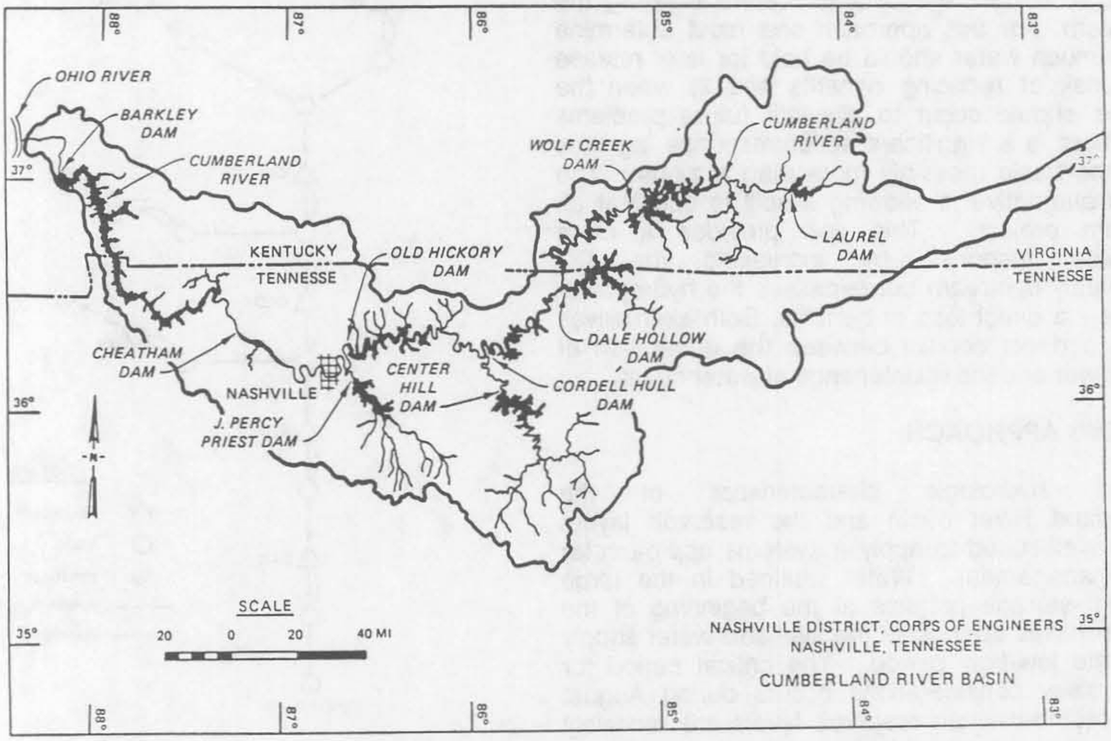

Figure 1. Location for the Cumberland River Basin

PROBLEM STATEMENT

The annual low-flow season in the Cumberland River basin provides a complicated scenario which is exacerbated by drought conditions. Natural stratification of the reservoirs begins during the summer months and continues into September, coinciding with the low-flow period. As inflows fall during the summer, outflows from the large storage projects also decline. Storage project releases during this period are sporadic on-peak hydropower discharges drawn directly from the hypolimnion of the storage pool with low temperatures, low dissolved oxygen (DO) concentrations, and relatively high oxygen demand. Since reaeration is limited during low flow, the quality of these waters undergoes little change as they pass almost directly into the hypolimnion of the downstream pool (Nashville District 1980). The problem becomes more acute as flow passes the city of Nashville where the waste load of the river increases. In previous years, DO deficits have been identified downstream of the Nashville area (Nashville District 1980).

POSSIBLE CORRECTIVE MEASURES

Two passive alternatives to alleviate the water quality problems exist. First, water conservation early in the season (i.e. before stratification) would allow more water to be released during critical periods. Increased flows would result in increased reaeration along the tributaries before entering the main stem. For this approach one must determine 1) how much water should be held for later release at the risk of reducing benefits and 2) when the releases should occur to alleviate future problems since there is a significant action/response lag time within the basin (possibly more than a month). The second alternative is allowing a spill to occur at an upstream project. This spill provides a more immediate response by increasing the DO immediately upstream but bypasses the hydropower turbines - a direct loss of benefits. Both alternatives involve a direct conflict between the generation of hydropower and the maintenance of water quality.

SYSTEMS APPROACH

The hydrologic characteristics of the Cumberland River basin and the reservoir layout make it well suited to apply a systems approach for water management. Water retained in the large upstream storage projects at the beginning of the summer makes up most of the available water supply during the low-flow period. The critical period for water quality considerations occurs during August and September when reservoir levels are relatively low, the reservoirs are stratified, and all releases are through the turbines and drawn from the hypolimnion. Therefore a management strategy to mitigate this critical period must begin much early. The management horizon must begin when the reservoirs are near full and continue until destratification is complete. A review of historical headwater data for the Cumberland projects shows that maximum heights are usually reached and maintained until approximately Julian day 150 of each year; the projects have historically undergone complete destratification by Julian day 270 thus suggesting a 120-day management horizon should be sufficient.

The arrangement of reservoirs in parallel and series within the Cumberland River basin provides a wide array of alternatives for allocating the available water as daily reservoir releases over the planning horizon. It is this large matrix of possible decisions which makes heuristic evaluation difficult and provides the impetus for applying mathematical optimization. A network representation of the basin is shown in Figure 2. The network takes advantage of the basin layout to minimize the links and nodes required to adequately represent the basin. Two links from each reservoir are used to represent discharges, one for spillway discharges (water quality benefits only) and the other for turbine discharges (hydropower benefits). The flow and water quality constituents are instantaneously mixed at the node below each dam.

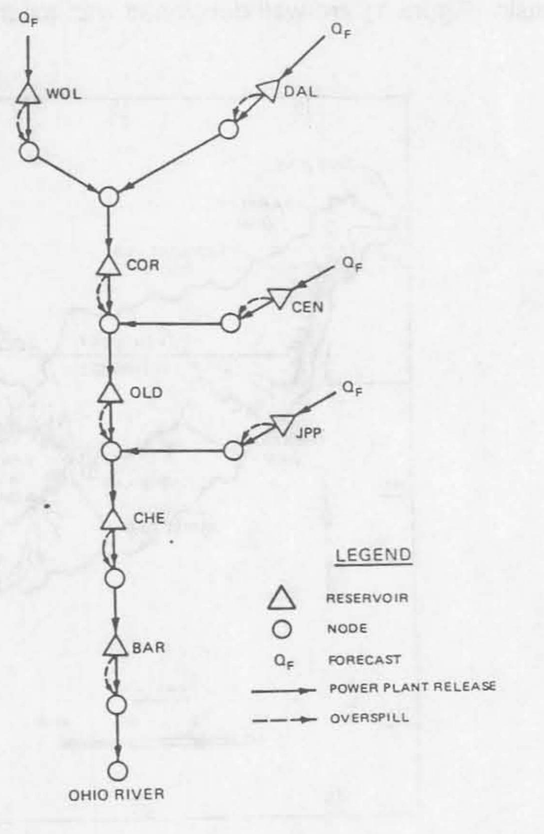

Figure 2. Network Layout for the Cumberland River Basin

PROBLEM FORMULATION

Converting the network layout to a formulation requires bounds on all state-space and decision-space variables and development of a performance index which encourages the operation to satisfy certain demands. Bounds on the state and decision variables are typically dictated by natural or imposed restrictions. The performance index, however, is developed by the engineer to make the system operate as desired. The general problem formulation is as follows:

$$\text{MAX} \quad f(U,X)$$

subject to:

$$S_{t+1} - S_t - RU_t + Q_t = 0$$

and

$$\begin{array}{ccc} U_{min} & U_t & U_{max} \\ X_{min} & X_t & X_{max} \\ C_{min} & C_t & C_{sat} \\ T_{min} & T_t & T_{max} \end{array}$$

where f(U,X) = function describing system benefits, U = system decisions (i.e. flows through each link), X = system state (i.e. headwater elevation for each node), S_{t+1} = storage in reservoir at beginning of next period, S_t = storage in reservoir at beginning of current period, R = routing matrix for inflows and outflows at current node, Q_t = local inflow during current period, C = DO concentration, T = water temperature, U_{min} = minimum flow requirements (for each link), U_{max} = maximum allowable flow (for each link), X_{min} = minimum headwater elevations for each node, X_{max} = maximum headwater elevations for each node, C_{min} = minimum DO concentrations, C_{sat} = saturation DO concentrations, T_{min} = minimum temperatures, and T_{max} = maximum temperatures.

The crux of any practical optimization problem lies in defining an appropriate performance index which properly reflects the goals and purposes of system operation. Developing a continuous function which accurately reflects the relative benefit of many variables is quite difficult. To compound the problem, generated benefits are often in different, non-commensurate units. This is particularly true of environmental quality benefits such as water quality and various forms of recreation. A possible approach to the optimization problem has been presented previously by the author (Hayes 1988) but it is by no means a complete solution. For the purposes of this paper, a general performance index function which represents all system benefits will suffice.

WATER QUALITY CONSIDERATIONS

Modeling water quality in a basin as large and diverse as the Cumberland River is a major undertaking. The purpose of this study is not to develop a large scale water quality model, but to demonstrate how optimization techniques can be used to better allocate water resources under limited-supply conditions. Consequently, existing empirically-based algorithms for routing the water quality constituents of interest, DO and water temperature, are being used. These 2-D routing algorithms have been calibrated for the Cumberland main-stem and are valid under a variety of conditions. Although the basis for these routing algorithms is quite simple by modern water quality modeling standards, they are perfectly adequate for a large scale simulation. The fast computation speed of these algorithms is also quite important for a large optimization model. The size and stratification characteristics of the storage reservoirs cause the temperature and DO levels to be much less dynamic; these values will be estimated from historical records.

OPTIMIZATION ALGORITHM

The highly dimensional, nonconvex, nonlinear nature of large scale multireservoir hydropower systems stretches the capabilities of commonly used mathematical optimization techniques. Hiew (1987) vigorously tested several optimization algorithms for application to such problems. The algorithms were evaluated based upon their speed and robustness in solving large scale multi-reservoir hydropower problems. Two algorithms, Optimal Control Theory (OCT) and Successive Linear Programming (SLP), performed particularly well. The results showed, however, that OCT is faster and requires less memory space, which are especially important for real-time operation. Based upon these factors, Hayes (1988) developed the general OCT formulation for the Cumberland River basin. Readers are referred to this reference for a detailed development of the optimization problem presented and solution technique.

APPLICATION

The model described in this paper will be implemented on a desktop personal computer for use in managing the Cumberland River system during low-flow periods. A initial management strategy will be developed from runs based upon forecast inflows and system state in early summer (about Julian day 150). The management strategy will recommend headwater elevation and release targets which satisfy the performance index set forth for the system. Periodic updates to the strategy, possibly even daily, can be made as the reliability of the forecast inflows improves and the system state changes. By initiating management alternatives early in the low-flow season, less drastic measures should be necessary late in the period.

CONCLUSIONS

Drought conditions can substantially effect water quantity and water quality in a well developed basin such as the Cumberland. The use of a real-time optimization model to consider management alternatives and system objectives can help counteract these problems. The Optimal Control Theory (OCT) algorithm can be used to determine optimum daily releases and has several advantages for use under these circumstances. For the algorithm to appropriately consider tradeoffs, however, the benefit obtained by meeting water quality objectives must be quantified. This quantification must be in commensurate units with other objectives such as hydropower generation so that rational tradeoffs are considered.

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