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MASS CURVE TECHNIQUE IN CONTROLLING A MULTIPURPOSE MULTIRESERVOIR SYSTEM — COUPLING A WATER QUALITY DESCRIPTION WITH AN INTERACTIVE SYSTEM

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ABSTRACT

The interactive BOX system, based on the mass curve technique of Varlet, has been designed for control of a multipurpose multireservoir system. The current version can handle a river basin with up to five lakes. The outcomes of objective functions for hydropower, flood control, recreation and water quality are computed and displayed using graphics. The system provides the manager with a facility of comparing the objectives interactively, and hence of iterating his decisions with regard to releases, until a satisfactory solution is reached. Commensurable attributes and algorithmic optimization are hence unnecessary. In this study, the focus is on the coupling of a dynamic water quality model with the BOX system.

KEYWORDS

Blue-green algae; flow regulation; interactive color graphics; mass curve technique; multipurpose management; multireservoir system; N/P ratio.

INTRODUCTION

In his exclusive review article on reservoir management models, Yeh (1985) lists and describes the mainstream approaches in contemporary literature. The approaches lean overwhelmingly on the philosophy of computerized operations research. However, a strong case can be made on the gap between methods suggested and conventions used in practice. This can by no means be claimed to be caused solely by practitioners, in that they are too conservative. Nothing is wrong with optimization as a technique, but a doubt arises, whether the formulation of a reservoir management problem in an OR frame should be emphasized in the magnitude done today.

There are several points in reservoir management tasks where a person even slightly involved in practice, might get concerned about the problem setting. First on choosing of the objective function. The optimization routines often require the presentation of the objective function in a form which is far too simple for describing the natural system in the complexity that should be considered. Very vague is quadratic objective function, since the solution depends greatly on scaling, and a steeply increasing marginal utility of attributes considered is assumed, even if in practical life the case is often quite the contrary. Usually also very incommensurable attributes are to be taken into account.

Consequently, the greatest restriction in the use of optimization lies apparently in the great complexity of the problems met in reservoir management, if the basin is not reduced only to e.g. energy production, but the river basin has also other values to that of an unipurpose production plant. For instance the curse of dimensionality of dynamic programming makes it practically impossible to approach multibasin multipurpose cases. What people need in such cases, instead of mathematically sound optima, is some support on how to manage the complex system they are dealing with.

A very traditional way of approaching a reservoir management problem is the mass curve technique. It has widely been accepted by non-scientific people. Here the classical graphical mass curve technique from the last century was computerized on a personal computer environment. Color graphics were used in an interactive framework. The FORTRAN-based graphical CAPLIB package by Resource Planning Associates, Inc., Cornell Research Park, Ithaca, NY, was used. An example is presented with 5 reservoirs and 4 uses.

MASS CURVE TECHNIQUE

Application of the mass curve technique to reservoir management was introduced by Rippl (1883). He plotted a mass curve Z of reservoir inflow x relative to reservoir draft q

$$Z = \int (x-q)dt = \int xdt - \int qdt = X - Q$$

and used it to find the smallest storage capacity K necessary to supply the desired draft without failure throughout the whole period under consideration.

During this century the use of the mass curve technique has been widespread especially in Europe where it has been used not only for the determination of storage for a given draft but also for other purposes, such as the determination of the draft or flood reduction corresponding to a given storage, hydropower plant operation for a given output, reservoir rule curves etc.

The usual way has been to calculate a sum of net inflows minus mean net inflow of the period, plot this on paper and draw another line at the distance of a storage volume beneath the plotted line. The upper line then represents the line of the empty reservoir, and the lower line the one of the full reservoir. A line describing a sum curve of outflows can now be drawn in the corridor formed by the storage lines. Varlet (1923) suggested that the optimum reservoir outflow pattern could be obtained by **the stretched-thread method**, i.e. by drawing the shortest possible line in the corridor.

Klemes (1979) demonstrates that in the case of the convex loss or concave gain function Varlet's method is still the best. It represents the limit to which both the dynamic programming and linear programming solutions converge. When comparing the mass curve method with methods of mathematical programming Klemes makes important remarks: **"What is a problem is that both methods**(of mathematical programming) **put analysis and result well out of the reach of any direct scrutiny by any 'back-of-the-envelope' computatios: One is left with little choice but to believe on the programmer and, above all, the computer... Perhaps the main practical virtue of the stretched-thread method is that it helps us to understand this umpleasant reality by displaying the mechanism of optimal reservoir operation in its most naked form stripped of the camouflage of spurious mathematics and technical jargon".**

Klemes admits that the stretched-thread method has its shortcomings. He points out: **"The simplicity and elegance of Varlet's solution are paid for by its applicability to only a rather specific optimization problem characterized by zero discount rate of future benefits and a simple form of univariate loss function".**

THE APPROACH PROPOSED

The approach proposed is based on the mass curve technique described above. The basic idea is that the operator is provided with an interactive computer tool, in which he can manually iterate the flow regulation scheme of a multi-reservoir multipurpose watercourse so that the outcomes of the attributes can be simultaneously seen on the screen. For this purpose, the stretched-thread method is not suitable. Instead, the user must draw the lines of cumulative outflows. Based on them and the resulting storage volumes, values of objective functions are calculated and displayed. The user can make changes to the policy until a satisfactory outflow pattern has been achieved. In this approach, no formal optimization is included.

The approach proposed can be used both in real-time control and in planning of regulation of a watershed. Forecasted net inflows are needed when real-time control is in consideration. If it is used for planning purposes the following studies may be included:

(1) Statistical distributions of historical monthly inflows and auto-correlations.
(2) Generation of inflow series (e.g.30 series, length 100 years).
(3) Application of the proposed approach for each series. Inflows, outflows and storage levels should be saved.
(4) Formation of outflows using multiregression analysis. Outflow may be dependent on inflows of preceding months, forecasted inflows and current storage levels (compare i.e. Young, 1967).

EXAMPLE PROGRAM

In this section, as an example of the approach, BOX program written for real-time control of five lakes is described (Figure 1). The attributes considered are energy production, recreational use, flood protection and water quality.

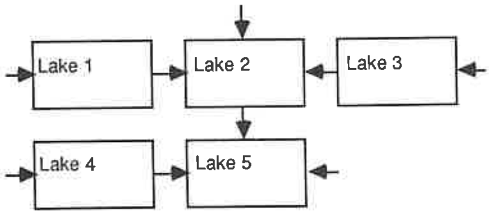

Fig. 1 Flow diagram of the five lake system of the example program.

The protocol of the program is as follows. After picking the menu item INPUT the computer asks the length of time for which the user wants to plan the out-flows. The current version can handle 200 time steps (days). Initial storage levels have been asked as well. In the example, the maximum storages are: For lake 1, $10 \cdot 10^6$ m^6; lake 2, $40 \cdot 10^6$ m^3; lake 3, $25 \cdot 10^6$ m^3; lake 4, $15 \cdot 10^6 m^3$; lake 5, $15 \cdot 10^6 m^3$.

The menu item SIMULATION draws mass curves for lakes the inflows of which are known (at the beginning, the lakes 1, 3 and 4). After planning outflows from lakes 1 and 3 a mass curve for lake 2 is calculated and displayed. When lakes 2 and 4 have been handled, a mass curve for lake 5 is drawn. The initial storage and the curve for the optimal water level with respect to recreation are displayed as well.

In order to plan outflows, the user must choose menu item PICK LAKE. The menu bar will disappear and after picking a box of a lake the mass curve will be zoomed. Also the maximum and minimum outflows are displayed. The menu item PICK LINE enables drawing the outflow mass curve. The maximum number of points picked is 20. By picking the reserved area on the left of the screen, a polyline is drawn through the picked points and outflows, water levels and values for objective functions are calculated.

On the next screen both the mass curve with the picked outflow mass curve and values of objective functions are displayed. The user has now two alternatives. If he is satisfied with the solution he can go back to SIMULATION (pick DONE) and pick another lake. If he doesn't accept the result he can try to improve it by choosing menu item NEW ATTEMPT and picking a new outflow line. In the example lakes 2 and 5 are provided with hydropower plants and flood can only occur downstream of lake 5. Using menu items ZOOM POWER and ZOOM FLOOD an enlarged picture of objective functions for lakes 2 and 5 can by displayed.

The values for objective functions are calculated using the following concepts. Water power is obtained simply P = 8.64 QH, where Q = outflow and H = hydraulic head. The flooded area is linearly dependent on outflow from lake 5 when exceeding the threshold value Q_{max}. Recreational losses are deviations from the optimum storage levels and are thus expressed in storage units.

After all the lakes have been handled the menu item SIMULATION displays both mass curves for all lakes and outcomes of the objective functions. If changes are needed, the user may reedit the phases he wishes.

Menu item SAVE saves the solutions. The best overall solutions with respect to power generation and recreation are saved automatically. Menu items SAVED, BEST POWER and BEST REC display the solution saved by the user, the best recreational solution, respectively.

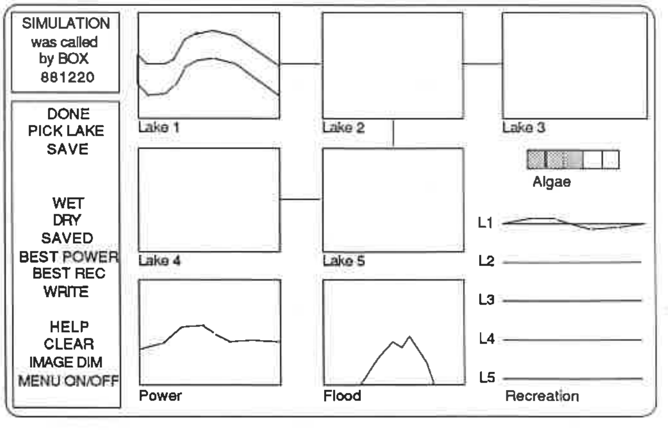

Fig. 2 A display outline showing menu options and layout of the screen. Mass curves and the objective function for recreation are shown for all lakes, although not drawn into this figure.

In order to take the hydrological uncertainties into consideration, the menu items DRY and WET are available. If WET has been picked, then greater net inflows are used, and DRY uses and displays the dryer alternative. Mass curves and inflows are based on those while mass curves of outflows are maintained. These menu items facilitate a simple sensitivity analysis of the solution. Changes on the solution are possible after each phase if needed. Standard error of inflow forecasts may be used as a basis when inflow values for wet and dry alternatives are under consideration. Menu item WRITE writes the current solution on the screen, i.e. outflows in m^3s^{-1} are shown.

WATER QUALITY DESCRIPTION

The impacts of flow regulation on the water quality of lakes is a very poorly known subject. There are a variety of factors driving the lake water quality, and on the other hand, the water quality attributes which are experienced to cause problems are bound very much to each specific case.

One of the most frequent water quality problems of lakes or reservoirs of the type considered in the example program is eutrophication. Varis (1989b) has studied the impacts of outflow regulation on formation of blue-green algal blooms in a polyhumic Finnish lake. The lake has an area of 16.4 km^2, catchment size of 1280 km^2, volume of $59.3 \cdot 10^6 m^3$ and residence time during floods about one week and mean 69 days. He found in simulation studies that it is only during the spring flood that the outflow regulation has a marked effect on blue-greens, even if the blue-green algal blooms do not usually occur until July or August. The overall pattern turned out to be the following: Increasing the water outflow with respect to the nominal 1980 situation is advantageous and after the flood peak disadvantageous when struggling against N-fixing blue-greens.

Based on the data by Stenmark (1982) also used by Varis in his study, a water quality description was set out for the example program. It is based on polynomial functions fitted to the data. In the example, the inflow to all the 5 lakes follows the same functional form. The magnitudes are proportional to the sizes of the catchments. An algal problem is assumed to form a nuisance at the lake 2. Nutrient concentrations are hence computed for the lakes 1, 2 and 3. The lakes are assumed to be continuously stirred.

TABLE 1 Rules used in evaluating the impacts of regulation strategies on the late summer blue-green algal blooms in lake 2. The rules are valid for the cumulative values of the considered variables over the period mentioned. Prefix NOM stands for nominal situation.

Period (Julian days)	Rules	Credit
0 - 100	-	-
100 - 120	IF(OUTFLOW=NOMOUT*0.8)	-1
	IF(OUTFLOW=NOMOUT*1.2)	1
120 - 140	IF(OUTFLOW=NOMOUT*0.8)	-2
	IF(OUTFLOW=NOMOUT*1.2)	2
100 - 140	IF(6<N/P_IN_INFLOW<11)	-1
	IF(N/P_IN_INFLOW<8)	-2
	IF(P_IN_INFLOW NOMP*1.1)	-1
140 - 200	-	

Based on the studies by Varis (1988, 1989a, b), the rules in Table 1 were formulated to give a rough insight into the impact of springtime flood regulation on the appearance of a blue-green algal bloom in late summer. The credits given to each rule are summed up and added to the credit of the nominal solution, -2. The number of negative credits is shown on the screen (Figure 2). If the credit is -5 or less, the rectangular indicator is blinking red implying that severe algal problems are to be expected. If the user wants to analyze more carefully the water quality impacts of the strategy chosen, he can pick the rectangle of the credits. Then the simulated phosphorus and nitrogen concentrations as well as the N/P ratio in lake 2 are displayed.

CONCLUDING REMARKS

There is no doubt that interactive color graphics offer new facilities for the use of personal computers in water management. The graphical on-line outcome on the screen helps the person planning and deciding on the management to understand how the computerized models behave and why they give the outcome they give. Also the heuristic comprehension of a practically trained manager can be effectively merged with mathematically formulated and conceptualized models on computer.

The operations research philosophy prevailing in modern literature but not really in contemporary practice of watercourse management, is likely to meet a new challenge in classical graphical techniques. Many of them are elegant in their intuitivity, and they may as computerized be subject to a renaissance.

The example program is without doubt a rough description of a (hypothetical) watershed. More knowledge is needed especially from the non-point source loading. However, it shows one way how to formulate an interactive management support model for a multipurpose multi-reservoir system. The practical experiences have shown that a user gets rapidly acquainted with the method and the computer program and that the solutions obtained appear reasonable. A problem of this dimensionality is unlikely to be approachable better by any off-line optmization oriented ways.

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