LAKE WATER LEVEL MANAGEMENT AS A TOOL FOR CONTROL OF THE LITTORAL ZONE: AN OPTIMIZATION APPROACH

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INTRODUCTION

The reduction of the littoral zone is used as a lake restoration technique that results in nutrient control and water quality improvement (Yount and Crossman, 1970; Burton et al, 1979;). In contrast, in other cases the littoral zone operates as a protective and pollutant filtering zone and its maintenance is desired (Tóth, 1972; Water Resources Management Program Workshop, 1986); in some cases also its protection as a freshwater wetland is desired. A number of studies and observations indicate that, in both cases, the fluctuations of the lake water level can be used as a management tool for controlling the littoral zone's existence and extent. (Jørgensen, 1983; Clausen and Johnson, 1990). The reduction or protection of the littoral zone requires totally different lake water level management during the year. The water balance of the lake and a number of constraints reflecting the specific characteristics of the system, the several water uses and the requirements for the protection or reduction of the littoral zone pose an optimal control problem.

Based on the above concepts, an optimization approach has been developed for management of the water levels in lakes and reservoirs where the littoral zone plays an important role. Inputs to the model consist of hydrological data for the watershed and the lake or the reservoir and data on water demand. The model can also be linked with an appropriate watershed model for direct input of hydrologic data. The objective function and the constraints formulations are based on the management purposes and on historical data concerning the status of the vegetation zone versus different water elevations. Model outputs are the amount of the water that must be released and the monthly averaged lake elevations during the year. The optimization model uses a dynamic programming algorithm. Detailed descriptions of the approach, sensitivity and testing of the algorithm for hypothetical cases are given in (Tsiros, 1987). The theoretical background of the approach is based on the results of a comprehensive field monitoring program presented and discussed extensively in (Jørgensen, 1983).

This paper describes the model's formulation, its major assumptions, and its application in a real case problem where impacts to the littoral zone have occurred because of a water development project. The applicability of the approach to regional reservoir planning and management, the limitations and further extensions of the approach are also discussed in the context of applying the proposed approach for management guidelines and recommendations concerning lake management with regard to lakeside vegetation zone control.

MODEL FORMULATION

Using a dynamic programming formulation, the deterministic optimal control problem can be modeled via the following set of mathematical concepts: objective function, state variables, decision variables and transformation equations. In this application, the stages of the problem are time periods. Considering the physical conceptualization of the system, it is convenient to discretize time into months which are the decision periods; the optimization horizon is the hydrologic year. State and decision variables are the lake elevations E_t and the releases X_t, respectively, with $t = 1,\dots,12$.

Objective Function

The formulation of the objective function is based on the results of some general observations (Jørgensen, 1983; Clausen and Johnson, 1990). The littoral zone will be maintained when the water level changes during the year meet two requirements: a relatively high water level with fluctuations during the winter and spring months and a low constant water level during the summer months. Therefore, the objective function can be stated as

$$\min \left\{ \sum_{t=k}^{l} [E_t - E_d]^2 \right\}$$

where E_t is the lake elevation at the t^{th} month, with $k \le t \le l$, k is the first month of the summer period, l is the last month of the summer period and E_d is the desired level during the summer period with respect to the littoral zone protection. Observations and historical data on water level measurements vs. the status of the vegetation zone are used to determine the desired level E_d during the summer period.

Constraints

The constraints of the problem reflect the maximum allowable lake levels with respect to the littoral zone protection during the year on a monthly or seasonal basis. Again, such information can be obtained from historical data. Generally, it is convenient to consider these constraints on a seasonal basis. Additional constraints would depend on the specific application. Operational requirements could provide also further constraints .

System Physical Relations

For a dynamic programming formulation the transformation equations are the physical relations of the system under consideration. Here, the physical relations express the hydrologic balance of the lake and also the lake specific relationship between lake elevation and lake surface.

A hydrologic balance model has been developed that is specifically adapted to the problem being studied. This model calculates the lake volume at each month t, t = 1,...,12 via simple continuity:

$$S_t = S_{t-1} + Q_t + P_t - IR_t - WD_t - EV_t - SP_t - X_t$$

where S_t is the lake volume at the beginning of the tth month, S_{t-1} lake volume at the (t-1)th month, P_t precipitation, Q_t surface runoff plus inflow from tributaries plus return flow, IR_t irrigation release, WD_t water supply release, EV_t lake evaporation, SP_t seepage losses from lake and X_t the amount of water to be discharged at the lake outlet at the tth month.

The approach requires also the mathematical relation of lake elevation vs. lake volume, which is a lake or reservoir specific curve. Usually this curve is given as a continuous piece-wise linear function. In case that historical records of storage are in terms of lake water surface - lake elevation, historical storage volumes can be extracted via appropriate stage - volume relationships. The relation is used to calculate the lake elevation at each stage t = 1,...,12 from the above described hydrologic water balance.

CASE APPLICATION

The optimization algorithm has been applied to a real case problem in order to examine the applicability of the proposed approach. The following measure has been used for the evaluation of testing results: the objective function value as computed by the model for one period must be close to the observed lake elevations during the same period. The lake Gyrstinge, Denmark was chosen for this testing because data required as input to the model were available. Additionally, model results can be compared readily with observed data. The data used as inputs to the model and information concerning the site description and the monitoring program were obtained from (Jørgensen, 1983).

The lake Gyrstinge has a surface area which ranges from 1.9 km^2 to 2.8 km^2 and a volume from 5.88 to 12.96 10^6 m^3. In 1974 the lake was changed from a natural lake to a reservoir and a pipeline was built to Lake Haraldsted 10 km away. The water of lake Haraldsted is used for drinking supplies. The outlet of the lake was regulated to be constant at 70 lit/sec. The impoundment allowed a water level about 2.50 meters higher. Marked effects have been observed with regard to vegetation zone, nutrient releases and dissolved oxygen balance. Prior to the regulation significant areas around the lake were covered by dense populations of reeds (Phragmites australis). The high water level after reservoir creation resulted in the destruction of the vegetation. To evaluate the effect on the reed zone, observations were made concerning the status of the zone during the different phases of filling the lake and compared with previous descriptions.

For a demonstrative test of the approach, data from two different periods have been selected. In the first test, for the year 1973, the model was applied using the optimization algorithm to simulate the management option when the littoral zone is desired to be maintained and protected. Average values based on historical data were used as the monthly inflow rates and the outflow rates were treated as the decision variable. The necessary constraints with regard to the littoral zone protection as were discussed previously, were also determined. Figure 1 illustrates the model results compared the observed data for the year 1973. For the second test, for the year 1975, the goal was to simulate the water level sequence after the reservoir creation. First the model was applied without using the optimization algorithm in order to mimic a lake management option when the vegetation zone was not wanted to be established or maintained. For this simulation the outflow rate was kept constant at a rate equivalent of 70 lit/sec; the results are shown in figure 2. Finally, the model was applied using the optimization algorithm to simulate an hypothetical management action for the protection of the littoral zone for the year 1975. Again the release rates were treated as the decision variable and the results are shown in figure 3. The results of the above tests indicate that if an optimum release schedule had been implemented after the reservoir was created, the vegetation would not have been destroyed. Given that some of the required data were not readily available, and considering that a number of assumptions were made, the results of the testing indicate the performance of the algorithm and the applicability of the proposed approach.

DISCUSSION / RECOMMENDATIONS

A number of studies indicate that the control of the existence and extent of the littoral zone can be implemented by water level management. In the context of a management approach, first the function of the littoral zone must be determined based on the specific characteristics of the ecosystem. By maintaining data such as water elevations records, observations on the status of the reed zone vs. different water elevations and also data for nutrients and sediments dynamics, the function and the value of the littoral zone can be evaluated. This evaluation together with the social and economic values of the zone can be used as criteria upon which should be based the decision about the protection or reduction of the littoral zone. Assuming that such a decision has been taken, the water level control can be used as a management tool. Additionally, recently the environmental impacts of water development activities (i.e. reservoir projects) have become the source of considerable concern. Given the need for satisfying population water demands, regional reservoir projects may cause irreversible adverse effects to ecosystems such as lakeside vegetation zone or lakeside wetlands. Assuming that the need of

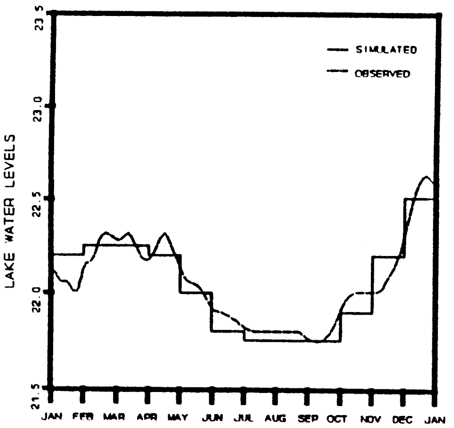

Fig. 1. Observed vs. simulated values for water levels (in m. above sea elevation) in the case of the protection of the littoral zone in year 1973

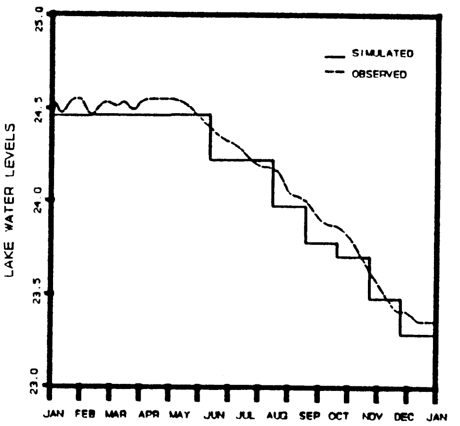

Fig. 2. Observed vs. simulated values for water levels (in m. above sea elevation) in the case of the destruction of the littoral zone in year 1975

a water development project has been evaluated, the water levels can be appropriately managed in order to avoid the effects on the littoral zone. Based on the above considerations, simple optimization models like the one presented here can readily simulate the system and predict release sequences when used in conjunction with historical data. Input to such a model consist of meteorological and hydrological data. For the formulation of the objective function and the constraints, information based on historical records concerning the status of the vegetation zone vs. the different water levels is required. Further, based on these results recommendations can be addressed concerning the water release schedule. General rules and recommendations can be stated. The reed zone will be established when the water level simulates the natural water level. The amount of water being discharged should be high during the winter and spring periods when also the inflows to the lake are high. A lower constant level should be maintained during summer. If reduction of the reed zone is desired, the degree of reduction depends on how different from the above schedule the water levels are to be managed. Destruction can be achieved when significant high water elevations are maintained during the year or if the reed zone is stressed by flooding and drying.

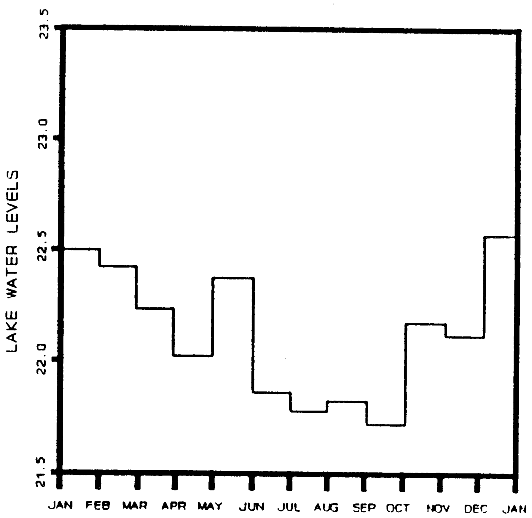

Fig. 3. Simulated values for water levels (in m above sea elevation) under assumption of an optimal management in year 1975

The major limitation of the optimization approach presented here originates from its assumption that the water level sequence is the dominant factor affects the littoral zone. Other factors also such as nutrient deficiencies, turbidity and pollution may play an important role on the dynamics of the littoral zone. Another limitation of the approach is the need for data from which quantitative information can be provided for the formulation of the objective function and the constraints. It is preferred that such data be site specific, because the value and the function of individual lakeside vegetation zones can vary greatly. However, data from similar systems can be used when the appropriate assumptions are considered.

Further research is needed for better understanding the role and the value of the littoral zone in lake systems; field studies also are required to assess quantitatively and qualitatively the influences of lake levels on the existence and the dynamics of the littoral zone. Methods are needed to predict the effects of the water level sequence on lakeside littoral zones.

Finally the following topics can be seen as extensions of the proposed optimization approach:
(a) incorporation of water quality constraints based on the water quality value of the vegetation zone and (b) generation of distributions via a stochastic framework to provide input variables for the water balance model, in order to include stochastic processes in the approach.

CONCLUSIONS

An optimization approach for management of the water levels in lakes and reservoirs where the littoral zone plays an important role has been presented. The major assumption of the approach is that the water level can be used as a management tool for controlling the littoral zone. The approach has been demonstrated for a real case problem, where the effects of the water level changes have been investigated with special emphasis on the littoral zone. Depending upon the specific system and also on the validity of the required assumptions the proposed approach may become useful in the area of lake management to determine optimal release sequences with regard to littoral zone protection; it can also be used to predict the effects on the littoral zone when small natural lakes are planned to change into impoundments.

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