Multi-Purpose Reservoir Operations Considering Reservoir Sediment

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Abstract

In planning, design or operation of reservoirs, engineers should consider the preventive measures which can be taken to reduce the amount of deposited sediment in reservoirs and to estimate its long-term useful storage capacity to be kept in the future for diverse purposes. Generally, there are three kinds of measures to manage reservoir sedimentation; 1) method of minimizing sediment deposition in reservoir; 2) method of maximizing sediment discharge through tunnel, or other outlets; 3) recovery of storage capacity by sluicing. In China, it has been commonly noted that the installation of bottom outlets is very important in preserving reservoir capacity, and so, their capacity to release sediment and the mode of operation should be considered in planning, designing and reservoir operation stages.

To derive optimal reservoir operation policies to manage reservoir sediment and water supply based upon 1), 2) or 3), Fenhe reservoir optimization model (FENHEDP) is developed. In this model, reservoir sediment is not treated as a state variable but as an information variable. A simulation model (FENHESIM) is developed based on the results of FENHEDP. The FENHEDP dynamic programming optimization model is being used to analyze the multi-objective problem to minimize reservoir sediment and water shortage. A unique aspect of this paper is the understanding of systematical reservoir sediment management. This approach for management of reservoir sediment has shown that water supply capability can be improved by multi-purpose reservoir operation which can minimize reservoir sediment and water shortage. The most important finding through this analysis is that sedimentation should be considered in objective function to increase water yield. The results show that the multi-objective function of water shortage and sediment deposit can improve water supply capability than a single objective function of minimization of water shortage do. This means the developed optimization model can provide reasonable reservoir management strategies for a heavily sediment laden reservoir system in the Yellow River basin in China.

1. Introduction

Because of the high urbanization and large-scale industrialization since 1960s, the demand on the domestic and industrial water consumption in Taiyuan of Shanxi province has been rapidly increasing. The water supply system of this project area looks very simple at present time. The main water sources are surface water for agricultural and ground water for domestic and industrial. The water demand has exceeded available supply, and as a result, groundwater has been significantly over pumped. Since there exist no raw water treatment plants, groundwater is the preferred source for domestic and industrial water needs. The groundwater has been overpumped and the maximum cone of depression now is more than 100 meters deep. The current amount of water demand is approximately equal to the total water supply of both surface water and groundwater. Therefore, the sources of water must be increased in the basin to meet the expanding future water demands.

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In addition, reservoir operating policies of the Fenhe No.1 reservoir, which is currently the only major reservoir existing upstream of the city of Taiyuan, are very complex because of reservoir sedimentation problem. The Fenhe No.1 Reservoir began operation in 1961 to provide for flood control, irrigation water supply and hydroenergy production. The mean annual inflow into the reservoir is approximately 350 MCM. The reservoir has a total storage of 720 MCM with 350 MCM allocated to sediment storage. The Fenhe River basin is part of the loess plateau in China, and therefore, the river is heavily sediment laden. By the end of 1992, the 350 MCM sediment storage in the Fenhe No.1 Reservoir is almost filled up. A sediment discharge tunnel is under construction at the reservoir to directly sluice sediment inflow in flood season and restore the active storage by scouring or eroding the deposited sediment during dry season.

By the time when a new reservoir and the Yellow River Diversion are brought on line in 1998, the available active storage in the Fenhe No.1 Reservoir will be further reduced. It is also projected that by the year of 2010, the future water demand will require the full capacity of the Yellow River Diversion. In the period between 2000 and 2010, it might be possible to use extra water in the system to sluice sediment through the Fenhe No. 1 Reservoir, since the sediment discharge tunnel is almost completed, the initial operation can be started immediately.

Studies carried out in China before show that sluicing of sediments can be effective to recover lost water storage (IRTCES, 1985). However, this requires that the reservoir stage be held at very low levels to exert the maximum scouring velocity on the sediment. It is also recommended to hold the reservoir stage at a low level so that flood season inflows can be released with sediment load and provide for additional scouring of the bed. In case of the Fenhe River basin, the flood flows are used to fill the reservoirs, if this flow is discharged to sluice sediment, there will be a possibility that the reservoirs might be filled up at a slower rate, but the demand might not be met. When the demand approaches the level of total basin supply, bypassing any water can potentially result in shortages.

However, from the perspective of systematical reservoir sediment management, the multi-purpose reservoir operation policies of the Fenhe No.1 reservoir can reduce reservoir sediment with increased water supply and sometimes possibly restore the reservoir storage. The multi-objective reservoir operation including reservoir sediment management can improve water supply capability and is better than a single objective function of minimizing water shortage in long-term operating strategies.

2. Fenhe Reservoir System Optimization Model

In order to find the best solution to minimize reservoir sediment and water shortage, a set of non-dominated solutions which show the tradeoff relationship between the considered objectives will be generated. The best solution will be selected from this explicit tradeoff relationship using heuristic approach or experiences. The dynamic programming algorithm (FENHEDP, modified based on CSUDP for sediment information variable, 1995) is used to find the optimal solution of multi- purpose reservoir problems. A weighting method is used to generate non-dominated solutions between reservoir sediment and water shortage. Sediment inflow term should be included in a variable of reservoir operation rules and some tradeoff relationship among objectives will be analyzed for decision making.

2.1 Objective Function

In real water resources systems, several objectives have to be considered simultaneously. The proposed objectives for this project are the water supply stability, which can be evaluated by minimizing water deficit, and the extension of reservoir life time, which can be estimated by minimizing reservoir sediment or maximizing sediment sluicing. But these two objectives are in conflict with each other. If a reservoir is to be operated to minimize water shortage, the reservoir sediment will be increased. and otherwise, the water shortage increases. So this problem has to be analyzed as a multi-objective optimization problem which have more than two objectives, and, for decision making to choose the best answer, a set of non-dominated solutions are to be generated which are composed of various optimal alternatives.

A "non-dominated solution" is also called "non-inferior solution", and is denoted as a solution with its one objective can never be improved without decreasing other objective values in multi-objective problems like the relationship between water supply and reservoir sediment. The best alternative is selected according to the view point of system analyst or decision maker to compromise between considered objectives. In this objective the accumulated reservoir sediment at the end of the operating stage will be considered as constraints of reservoir minimum storage volume and it will be compared with reservoir storage volume at the end of the operating stage.

The objective of minimizing water deficit is to minimize the variation from target year water demand using square method to distribute water shortage equally. However, to fill highly sediment laden flood water into reservoir is likely to reduce capacity-yield relationship in view of long-term operation. In contrast, discharging whole flood water to sluice sediment will cause a severe water shortage. However, according to adopted reservoir sediment control operation policies, water supply capability and reservoir life time can be improved based upon reservoir capacity-yield relationship. The objective function to achieve the goals can be formulated as follows;

$$\text{Min} \sum_{i=1}^{N} W_1 F_1 + F_2 \quad \text{------(1)}$$

$$F_1 = \sum_{n=1}^{M} \underline{DS}_m \quad \text{------(2)}$$

$$F_2 = W_2 \sum_{n=1}^{N} (DW_{i,n} + 5.)^2 + W_3 \sum_{n=1}^{N} (IW_{i,n} + 5.)^2 + W_4 \sum_{n=1}^{N} (AW_{i,n} + 5.)^2 \quad \text{------(3)}$$

$$\underline{DS}_i = h(U_i, X_i, X_{i-1}, \sum_{i=1}^{i-1} \underline{DS}_{i-1}.) \quad \text{------(4)}$$

$$X_i \geq \sum^{i} \underline{DS}_i + 10. \quad \text{------(5)}$$

$$U_i = X_i - X_{i-1} + I_i - E_i - L_i - D_i \quad \text{------(6)}$$

$$X_{i\,min} \leq X_i \leq X_{i\,max} \quad \text{------(7)}$$

$$U_{i\,min} \leq U_i \leq U_{i\,max} \quad \text{------(8)}$$

Where, F is the performance index, F_1 is the objective variable for sediment, F_2 is the objective variable for water supply, W_1, W_2, W_3 and W_4 are the weighting factors for each objective, DS_i is the deposited sediment at stage i, $DW_{i,n}$ is the domestic water deficit at stage i at water supply gage point n, $IW_{i,n}$ is the industrial water shortage at stage i at water supply gage point n, $AW_{i,n}$ is the agricultural water shortage at stage i at water supply gage point n, i is the stage number and n is the water supply gaging point number. U_i is the amount of water released at stage i, X_{i-1} is the beginning storage at stage i, X_i is the ending storage at stage i, I_i is the unregulated inflow into reservoir at stage i, E_i is the evaporation loss at stage i (a function of the beginning storage and the ending storage), L_i is the seepage loss at stage i (a function of the storage), D_i is the diversion at stage i and m is the number of reservoir.

In consideration of Chinese counterparts' opinions, the weighting values of the domestic and industrial are given first priority and the second priority is given to the agricultural. The last is reservoir sediment. Five combinations of objective function weighting values for each objective are considered. In order to generate the tradeoff relationship between sediment and agricultural water shortage, a so large weighting value is given to the domestic and industrial that it is dominating and could not be affected by varying other objective values. The model is run based on varied reservoir minimum storage bound for one-dimensional problem and the Yellow River Diversion volume for multi-dimensional problems. In Eq.(5) the minimum storage for fishery or wildlife is given as 10 MCM.

2.2 Reservoir Sediment Sluicing Efficiency

The purpose of regulating the flow by a reservoir during the flood season is to release as much sediment as possible from the reservoir by making use of the silt carrying capacity of the flood. Generally, the regulation of flow is achieved by lowering the water level during the flood season by operating the low-level or bottom out-lets under controlled or uncontrolled conditions. During the period of high water level of floods in a detention reservoir, the outflow silt discharge is always smaller than that of the inflow, as a result of the backwater effect .

In fact, drawing down the water level in a reservoir to reduce the amount of sedimentation, or to induce erosion of the deposited sediment to recover storage capacity, is a method often used in reservoirs, especially those of hydroelectric power stations. The efficiency of sediment flushing depends on the topographic characteristics of the reservoir, the capacity of the outlets, the outlet elevation, the characteristics of the inflowing sediment, the mode of operation, the time duration of flushing, and the flushing discharge, etc.

However, since the operating time step of the development optimization model is based on monthly basis in dry season and on 10-day basis in flood season, which ignores whole reservoir situation related to sediment discharge and deposit form, etc., the accumulated sediment deposit volume in Eq. (2) can be calculated as deposition of each stage through the following equation,

$$DS_i = DS_{i-1} + IS_i - \eta_i IS_i = DS_{i-1} + IS_i(1-\eta_i) \quad \text{------------------------------------(9)}$$

Where, DS_i is the accumulated sediment volume at the end of the stage i, DS_{i-1} is the accumulated sediment volume at beginning stage i, IS_i is the unregulated sediment inflow volume into reservoir at stage i, η_i is the sluicing efficiency at stage i. It could be decided through empirical flood detention time versus sluicing efficiency curve.

$$\eta = f\left(\frac{XA_i\, IR_i}{UR_i^2}, D_{50}, S\right) \quad \text{--(10)}$$

Where, XA_i is the average storage capacity below the highest water level during the passage of the flood, IR_i is the average inflow rate (m^3/sec), and UR_i is the average outflow rate (m^3/sec), D_{50} is the median diameter of the suspended load carried by the flood (mm), S is the sediment specific weight of average sediment concentration of the flood flow (kg/m^3).

3. The Applications of the Reservoir sediment Management Model

The storage function of reservoirs is to assure a better supply of water for users and consumers compared to withdrawal directly from natural river reaches. The design of a reservoir, therefore, depends mainly on the needs to be met and on the water sources available. Since there are many variables to be considered in the Fenhe River Reservoir system, it is not easy to get a correct answer. Because the Fenhe Reservoir system is not only very complex but also involves too many objective variables. In addition, demand for water will exceed available surface water supply if there is no Yellow River Diversion. The analysis strategies of the developed optimization model to cover these goals can be classified as follows in respect of the time horizon decided by the status of available water resources.

In order to generate a general tradeoff relationship between the water yield and the reservoir sediment, the developed model is run. The analysis steps can be classified as three steps according to the target years. The first step is to estimate the water supply capability and reservoir sediment volume of Fenhe No.1 Reservoir only until Fenhe No.2 Reservoir and the planned

Yellow River Diversion Project are completed in 1998 and brought on line. The second step is to appraise water supply capability according to increasing water demand and changing of the reservoir system after the completion of the Fenhe No.2 Reservoir and the Yellow River Diversion Project. The third step is to estimate water yield after the completion of the Fenhe No.3 Reservoir.

According to the results of the Fenhe No.1 Reservoir operation shown in Figure 1, the sensitivity of water shortage increases sharply as the deposited sediment volume decreases, when reaching a certain point the deposited sediment does hardly increase with increasing water deficit. This happens for both high and low level bounds. It should be also noted that reservoir sediment deposition increases with increasing reservoir minimum bound. The most important finding through this analysis is that in addition to passing total sediment inflow, the deposited reservoir sediment can be abraded during flood season, namely, the sluicing efficiency can sometimes be greater than a unity. In Figure 1, the upper point of each curve is the optimal point derived from single objective function (minimizing water deficit, the weighting value for sediment is zero), by comparing this point with the other points which stand for the non-dominated solutions derived from multi-objective function, it can be interpreted that the multi-objective function of water shortage and sediment deposit can improve water supply capability and is better than a single objective function of minimization of water shortage. This means the developed optimization model can provide a reasonable output for the reservoir sediment control. The deposited sediment in the Fenhe No.1 Reservoir is estimated to be 53.73 MCM during the six years from 1993 to 1998. The sluicing efficiency can be raised to 25.77 % which is more than 20.55 % than the present level.

These kinds of phenomena can be seen in Figure 2 which represents a multi-dimensional operation. For joint operation of the Fenhe No.1 and No.2, the time series of input variables is divided into three ten-year time series. The results for decision-making are based on average value of the three simulated results. The analysis procedure to obtain tradeoff relationship among water shortage, deposited sediment and the Yellow River Diversion is obtained using the three series. The multi-objective based on weighting method like that in the above-mentioned one-dimensional operation is adopted for the multi-dimensional analysis. According to the results shown in Figure 2, the sensitivity of water shortage increases as the Yellow River Diversion volume decreases, the deposited sediment shows large difference between single objective for water supply and multi-objective for water supply and reservoir sediment. But in case of multi-objective, the sensitivity of reservoir sediment deposit is not high. For water-supply capability, multi-objective for minimizing water shortage and sediment deposit is less than that of single objective for minimizing water shortage. The trend of sensitivity between single and multi-objective clearly shows that multi-objective can improve more water supply capability than that of single objective with a decreasing the Yellow River Diversion.

Concerning the reservoir operating rules, two kinds of operation policies are developed. In dry season, the releases will meet the water demand using all available water as shown in Figure 3. and in flood season, there are two criteria as shown in Figure 4. The water inflow and the sediment inflow must be checked to decide release volume. If these two value are much more than some criteria, the release will be decided based upon the developed reservoir operating rules. The assumed criterion for inflow is 40-60 MCM/MONTH and for sediment is 2 MCM/MONTH. The simulated results by FENHESIM are compared with the results by FENHEDP. The difference between these two results is less than 10 %.

4. Conclusions

This study proved the possibility of reservoir sediment management using sediment dynamic programming model (FENHEDP) and simulation model (FENHESIM). This kind of analysis is very useful to reservoirs built on the Yellow River basin. In this project the developed model will be used very successfully to develop reservoir operation policies for the Fenhe Reservoir system and decide the size and construction time of the Fenhe No.3 Reservoir.

Reference : IRTCES, Lecture Notes of the Training Course on Reservoir Sedimentation, International Research and Training Centre on Erosion and Sedimentation, Beijing, China, 1985.

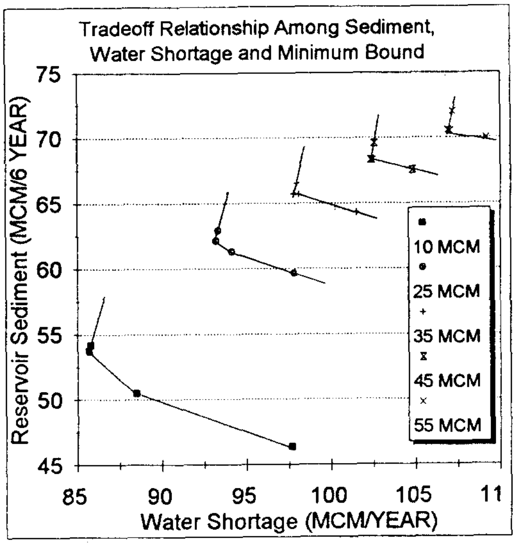

Fig. 1 Tradeoff Relationship Among Sediment, Water Shortage and Minimum Bound by the Fenhe No.1 Reservoir

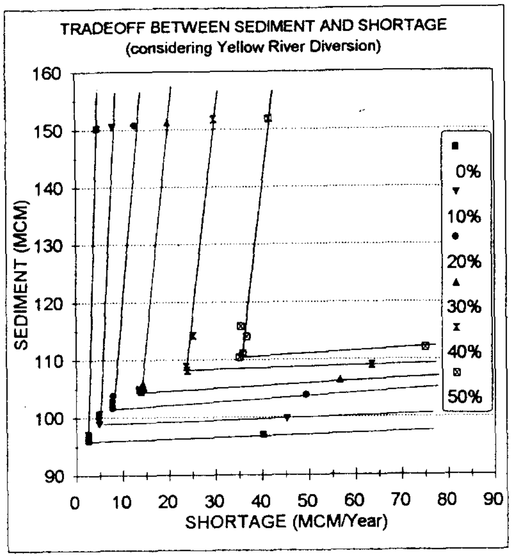

Fig.2 Tradeoff Relationship Among Sediment Water Shortage and Yellow River Diversion by Two-dimensional operation (No.1 ans No.2)

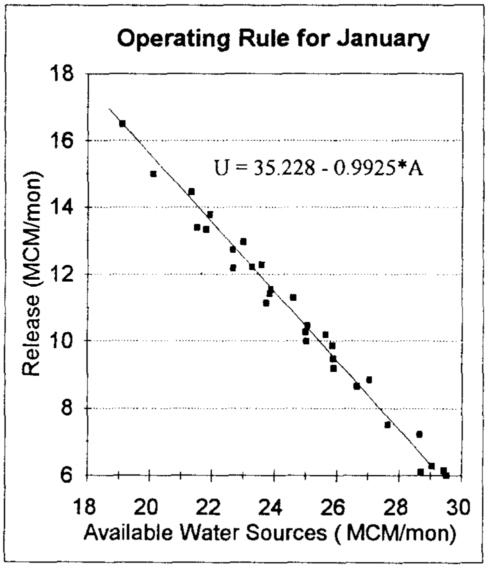

Fig. 3 Reservoir Operating Rule for Dry Season (January)

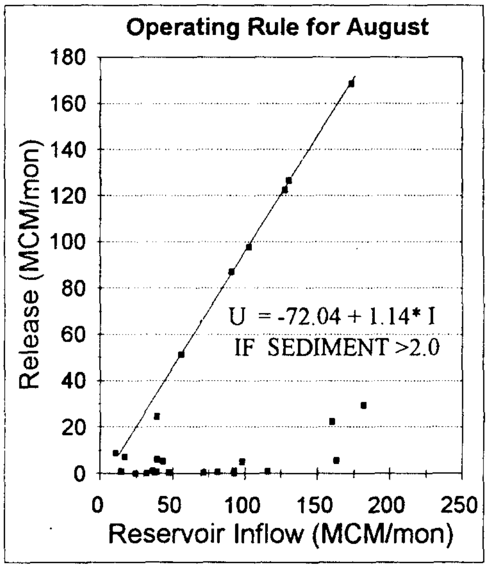

Fig.4 Reservoir Operating Rule For Flood Season (August)