Development of Information Variable Dynamic Programming to Consider Reservoir Sediment Management

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Abstract

Various mathematical models are being used to solve the water resources management problem in Taiyuan city, the capital of Shanxi Province, China. The most successful one among these mathematical models is a reservoir sediment management model called FENHEDP which is based upon modifications on INCDP of CSUDP. The developed FENHEDP includes a mass balance which can take account of reservoir sediment deposition employing a sediment sluicing relationship. The sediment deposition provides additional 'INFORMATION' about the reservoir as a function of the volume state of the reservoir, therefore, it can be handled as an 'INFORMATION VARIABLE' rather than a state variable. The sluicing efficiency curve has been developed in Yellow River basin. This sediment sluicing relationship predicts the amount of sediment discharge as a function of reservoir volume and discharge rates of inflow and outflow.

This model will adopt a multi-objective function with objectives of both minimizing total reservoir sedimentation and minimizing water shortages. The FENHEDP model has been run to derive the Fenhe No.1 single reservoir operation policies, and joint operation of the Fenhe No.1 and No.2. This model will be run for various sizes of the proposed Fenhe No.3 reservoir to decide its optimal size and construction time. To make sure that the model is reliable, various verifications have been carried out in order that the modifications made to the FENHEDP code is functioning correctly. The tests of this modified FENHEDP code show that it is working satisfactorily. In addition, the real reservoir operating results show that the developed models can provide a good reservoir operating policies for reservoir sediment management and water supply. So this version can be a typical model for reservoirs located on the Yellow River basin.

1. Introduction

The sediment management in reservoirs constructed on rivers in China is one of the most important problems to extend reservoir life in view of scarce affordable dam sites in the future. As is known to all, the life of hydraulic structure depends much upon its adopted operation polices which can dictate the sediment situation in it, and conversely, the deposited sediment can affect originally adopted operation polices. Take reservoirs located on the Yellow River as examples, the reservoir operation policies have been in fact changed significantly because of reservoir sedimentation. Silting of impounding reservoirs seriously threatens the life time of them. Since the sites suitable for dam construction become more and more rare the sedimentation problem is ever so pressing. It is documented that Laoying reservoir in Shanxi Province was completely filled up with sediment by a flood even before construction of the dam was completed (IRTCES, 1985).

Since the 50s, construction of multi-purpose hydro-projects have been carried out on a vast scale in China; thus, great attention has been given to the problem of reservoir sedimentation by engineers. Much emphasis has been placed on the collection of field data, and special field stations or survey teams have been set up at a number of reservoirs, including the Sanmenxia Reservoir on Yellow River, the Danjiangkou Reservoir on Han River and the Guanting Reservoir on Yongding River. Regular surveys are conducted before and after the flood season every year, and an additional survey is required after the passage of a major flood. Though the development

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of the reservoir sedimentation is now better understood, the point is yet to be reached when a mathematical model may be readily used to manage reservoir sediment.

This problem arises in the Fenhe River Basin Water Resources Development Project with no exception. The Fenhe No.1 Reservoir with a capacity of 720 MCM, is the largest reservoir on Fenhe River as shown in Figure 1, which is one of the main tributaries of Yellow River. From its initial operation in 1962 to the year of 1992, the deposited sediment volume is over 350 MCM. If the reservoir is to be operated in present operating way, the available active storage will be further reduced, and in fifteen years, the total capacity will be filled up. For these reasons, the structures to prevent reservoir sedimentation have been continuously constructed in the Fenhe No.1 Reservoir. At present, a sediment sluicing tunnel with a diameter of 8 meters and a length of 1 km is under construction along the dam shoulder. The Fenhe No.2 Reservoir is currently under construction downstream of the Fenhe No.1 Reservoir. It has sediment sluicing tunnels five meters above the river bed. If the reservoir is operated with a sluicing efficiency of 60 %, the life time of this reservoir is expected to be 20 - 30 years. The Yellow River Diversion now under construction will bring in a yearly sediment inflow of 0.8 MCM. This diversion project will be operated 10 months a year to provide an additional 640 MCM to the Fenhe River.

The tasks of this project are to appraise water yield and predict sediment deposit volume of the Fenhe Reservoir system and decide the most appropriate size and construction time of the Fenhe No.3 Reservoir. To solve these problem, mathematical models were developed. The main accomplishment of the developed models, until now, is a reservoir sediment management optimization model FENHEDP which is bottomed upon modifications on subroutine INCDP in CSUDP to handle reservoir sediment state as an 'INFORMATION VARIABLE'. The preliminary analysis shows that the developed FENHEDP based upon the use of the sediment sluicing relationships can provide the best answer to the Fenhe Reservoir system's optimal operation to minimize water shortage and reservoir sediment.

2. Information Variable DP

2.1 The Recursion Equation of Information Variable DP

Treating sediment volume as a state variable is not the best way of incorporating it into the FENHEDP model. Conceptually, each state variable should be relatively independent of the other state variables. However, the sediment volume in a reservoir will be a direct result of that reservoir's operational decisions. It is completely dependent on the state of the reservoir. Therefore it does not really define a unique "state", instead it provides additional "information" about the reservoir as a function of the volume state of the reservoir. It can be directly handled as an "information variable" rather than a state variable. This approach is not only more theoretically correct, it also significantly reduces the computational requirements of the DP, giving computational requirements that are only slightly larger than those of a pure 3-dimensional DP.

The General Recursion Relation formulation of the forwards DP problem for the Fenhe river system including sediment is shown below:

$$F^*_i\{X_i, \underline{DS}_i(X_i)\} = \underset{X_{i-1}}{\mathrm{MIN}} \left[f_i\{U_i, X_i, X_{i-1}, \underline{DS}_{i-1}(X_{i-1})\} + F^*_{i-1}\{X^*_{i-1}, \underline{DS}^*_{i-1}(X^*_{i-1})\}\right] \text{ -----------------(1)}$$

subject to:

$$U_i = g(X_i, X_{i-1}) \text{ -----------------(2)}$$

$$\underline{DS}_i = h(U_i, X_i, X_{i-1}, \underline{DS}_{i-1}) \text{ -----------------(3)}$$

$$X_i \geq \underline{DS}_i \text{ -----------------(4)}$$

$$X_{min} \leq X_i \leq X_{max} \text{ -----------------(5)}$$

$$U_{min} \leq U_i \leq U_{max} \text{ -----------------(6)}$$

where, F_i is the optimal value function at stage i, X_i is the state vector of reservoir storage volumes at stage i, $\underline{DS}_i(X_i)$ is the information vector of reservoir sediment volumes, one sediment volume per reservoir where each sediment volume corresponds to a unique reservoir storage volume, $f_i(.)$ is the stage return function, g(.) is the state variable transition function for reservoir release, h(.) is the information variable transition function for the sediment accumulation function, is the decision vector of reservoir release volumes at stage i.

In this formulation, the information vector is calculated at each stage as the calculations proceed forwards in the forward DP. Consider, as an example, the situation for a single reservoir. Starting at stage 1, the DP model will evaluate feasible combinations for beginning and ending storage for that reservoir. For each combination of beginning and ending reservoir storage, $X_{1,i-1}$ and $X_{1,i}$, a unique volume of sediment will be deposited. Therefore each ending storage, $X_{1,i}$, has a corresponding sediment volume, $DS(X_{1,i})$. The sediment volume DS should be stored as a function of $X_{1,i}$. In the DP only the optimal values of $X^*_{1,i}$ are stored and therefore only the values of DS corresponding to these optimal values $X^*_{1,i}$ need to be stored for the next stage.

At stage 2, the optimal values of $X^*_{1,i}$ from stage 1 become the values of $X_{1,i-1}$ for stage 2. Therefore, the stored values of sediment deposition at the end of stage 1 become the initial sediment volumes for the calculations in stage 2. At the end of stage 2, the optimal output states and their associated sediment deposition volumes are stored for use in stage 3. It is important to notice that the sediment volumes, DS, are being updated at each stage and that the value of DS at the end of a stage is only a function of the value of DS at the beginning of that stage. Therefore only two values of DS need to be stored at any one time. This reduces the amount of information that must be stored in computer memory. For the multi-dimensional case of three reservoirs, the basic concept is the same as the single reservoir example above, except that "information vectors" are used to store a value of sediment accumulation for each of the three reservoirs. This calculating procedures are shown in Figure 2.

The multi-dimensional computations within the FENHEDP model are based upon the CSUDP model developed at Colorado State University. The CSUDP model does not provide for storing and carrying forward an information vector in a multi-dimensional problem. Modifications were made to Subroutine INCDP. Subroutine INCDP is used in the FENHEDP model to perform the multi-dimensional DP calculations. New variables were defined to store the accumulated sediment deposition as a function of the storage levels in each of the three reservoirs. As the DP moves forward through the stages, the appropriate sediment volumes are transferred to the next stage. Only two stages of sediment volumes are stored. These are continuously over written as the DP proceeds. This is done to reduce computer storage requirements. Once the optimal solution has been found, the traceback process is used to determine the optimal storage levels and releases at each stage. This traceback works from the last stage backwards to the first stage. However, the calculation of sediment deposition can not be made backwards. Therefore the optimal solution from the traceback is used to make an additional forwards calculation through the stages to calculate the optimal reservoir sediment volumes.

2.2 The Verification of Information Variable DP

Since the logic of Subroutine INCDP is so complex, intermediate printouts were made to check the storing and transferring of the values in the information vector for sediment deposition. To verify that the modifications to the FENHEDP code were functioning correctly, a simplified problem with 2 reservoirs and 3 stages was formulated and solved manually using a spreadsheet. The same problem was solved with the modified FENHEDP code and produced exactly the correct results. The FENHEDP code was further tested by comparing the sediment accumulation from the DP with the sediment deposition produced by the FENHESIM model using the same values of reservoir storages and releases. The answers were exactly the same. Various other tests were made by varying the weights in the objective function and considering all other penalty functions. In all tests the modified FENHEDP code appeared to work correctly.

One-dimensional version of the FENHEDP model to consider sediment accumulation is also modified. The one-dimensional version of the FENHEDP model is used to evaluate a single reservoir of the Fenhe River Reservoir systems. Using the modifications made for the multi-dimensional DP as a guide, the one-dimensional model is modified and tested. All tests of this version of the model show that it is working correctly.

2.3 The Verification of Sluicing Efficiency Curve

The sluicing efficiency curve being used for calculating sediment discharge rate can be verified in two ways. The first way of verification is to compare between the observed data and the simulated result. In the simulation, 21 years' reservoir operation data from 1962 to 1982 are used and one empirical sluicing efficiency curve, shown in Figure 3, is employed. The verification result as shown in Figure 4 shows a good matching, and furthermore, the sluicing efficiency curve developed from empirical data shows some peculiar characteristics. The sediment grain diameter is D_{50} and the flood detention time is very short in the original curve, say two or three days, but through developed model run, it is understood that the sluicing efficiency curve is adaptable both on a 10-day basis and on a monthly basis. This means the sluicing efficiency curve adopted for this study can be used in long-term reservoir operation model, especially monthly and 10 days operation. The second way of verification is to be done by comparing the results of model runs of the developed models and a more sophisticated reservoir sediment model, called Zhang`s model, which is to be used to improve the general sediment sluicing efficiency curves adopted in the FENHEDP and FENHESIM.

3. The FENHEDP and FENHESIM

The Fenhe River Reservoir system can be divided into two parts; one is ground water, and the other is surface water. The surface water (reservoir) system can be regarded as a 3-dimensional system which is serially connected. The existing Fenhe No.1 Reservoir is located between the other two reservoirs. The Fenhe No.2 Reservoir is under construction downstream of Fenhe No.1 Reservoir near Lancun where a very famous ground water plant is located. The Fenhe No.3 Reservoir, which will be operated to regulate diversion water from the Yellow River Diversion Project, will be located at one dam site chosen from Haoshuigou, Shijiazhuang and Xiajingyou dam site alternatives, . The ground water system is consisted of many kinds of ground water supply systems. Especially, Jinci and Lancun springs are two of the most famous ground water sources and there are four types of groundwater sources exist as follows; 1) Eastern Limestone aquifer; 2) Western Limestone aquifer; 3) Northern Limestone aquifer; 4) Jinzhang Limestone aquifer. But over exploitation of ground water has caused ground water level drawdown and phreatic aquifer has dried up, the ground has settled. Taiyuan water resources system considered in this study is limited within upper basin of Fenhe River and focuses on surface water as shown in Figure 1.

A schematic diagram of the Fenhe River system (Figure 5) shows all three reservoirs, the Yellow River diversion, water management districts 11 - 14, and a lumped demand downstream of the First Fenhe Weir. Each major inflow point and diversion should be considered as a node on the diagram. Direct diversion from the Fenhe No.1 Reservoir (D_{12}) is connected to Gujiao city where a coal mining area is located. Except diversion to Gujiao, all diversion from river will be very small. The diversion to Taiyuan city is considered from the first weir as a most downstream gage point of the schematic diagram. Because this diversion to Taiyuan city covers whole demand downstream, the water demand can be considered as a lumped demand.

At each reservoir, evaporation and seepage is considered as a function of water surface area and storage volume. And at each intervening channel reach, seepage and local inflow also are evaluated by its mass balance equation. One of the important element of this system is sediment discharge tunnel at the each reservoir. Since the sediment discharge tunnel is still under construction, its effectiveness is not yet known. In this system the developed model will consider the sediment discharge tunnel of the Fenhe No.1 Reservoir, though ground water and sedimentation were not considered in this diagram. Ground water demand and supply upstream of Taiyuan city seems to be much smaller than demand from Taiyuan city. And it can not be simulated in the developed models because of difficulty to calculate the mass balance between surface and groundwater without a well built model. Deposited sediment is considered as a information variable rather than a state variable.

The FENHEDP dynamic programming optimization model was developed based on the aforementioned schematic diagram. Separate groundwater simulation models are used as input into the model. The FENHEDP model is run 20 stages a year. Monthly time steps are used for eight non-flood months and 10-day time steps are used for the four flood months. A multi-objective function which takes account of objectives of minimizing total reservoir sedimentation and minimizing water shortages is formulated. The FENHEDP model is being run for various sizes of the proposed Fenhe No.3 Reservoir and combinations of the two objectives to develop the tradeoff relationship between managing reservoir sedimentation and minimizing downstream water shortages. The state variables and the decision variables obtained from FENHEDP will be used for operating rules of simulation model.

The mass balance simulation model of the three reservoir system, called FENHESIM, was developed under the same circumstances as in FENHEDP model. This model uses the same system equations as the DP model. The purpose of this model is to test the monthly operational policies developed from the optimization model and refine the size and the construction time of the Fenhe No.3 Reservoir. This model can be run on a 10- day basis or even shorter time basis, say daily, and it will be used to provide detailed release and sediment accumulation information. The calculated reservoir releases and storages will be evaluated using a more detailed sediment deposition model called Zhang's model. The general interconnection of the models is shown in Figure 6.

4. Conclusions

This project certainly has a unique technical task which is to consider reservoir sediment management using information variable. The FENHEDP's preliminary results of the one-dimensional problem for the Fenhe No.1 Reservoir and the multi-dimensional model analysis for the joint operation of the Fenhe No.1 Reservoir and the Fenhe No.2 Reservoir are very positive and it appears that the developed system of models is adequate to properly size the proposed reservoir and develop integrated system operational policies. The model tests for optimal reservoir sediment management show improved operation of Fenhe reservoir system to minimize active storage loss in a long-term operation planning. The developed FENHESIM using operation rules obtained from FENHEDP also can provide daily-based reservoir operation policies for sediment management and water supply.

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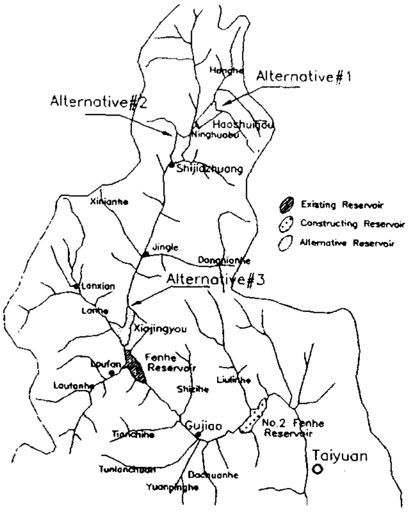


Fig. 1 Upper Fenhe River Basin

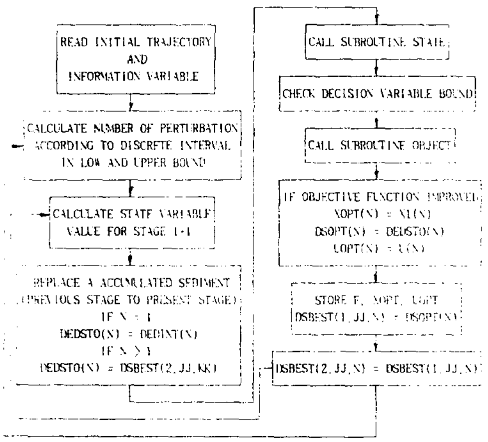
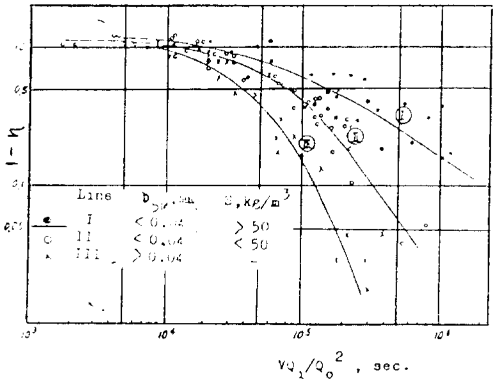


Fig.2 Tracing Procedure of Information Variable in INCDP



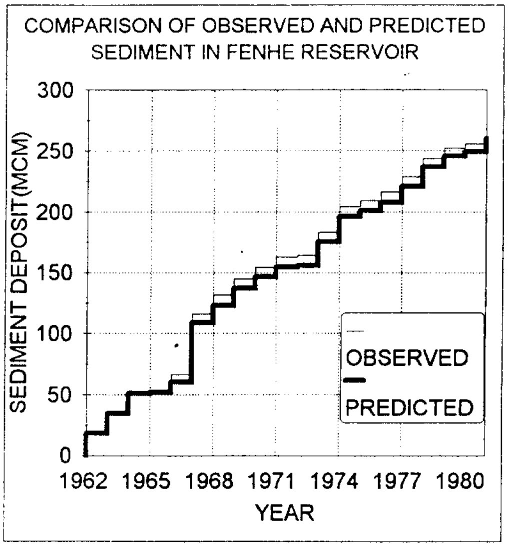
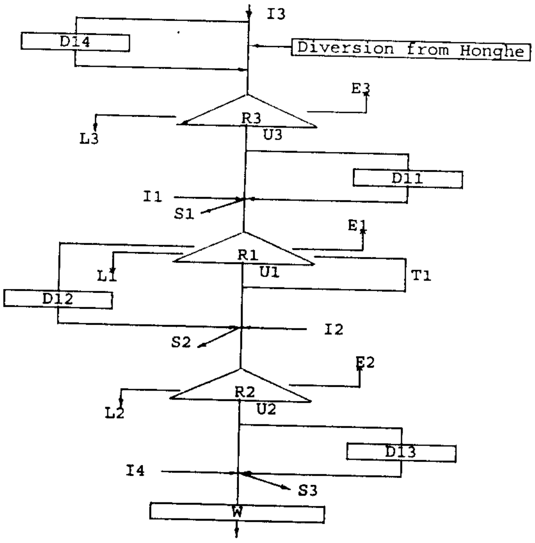


Fig. 3 Sluicing Efficiency Curve

Fig.4 Verification of Reservoir Sediment Sluicing Curve



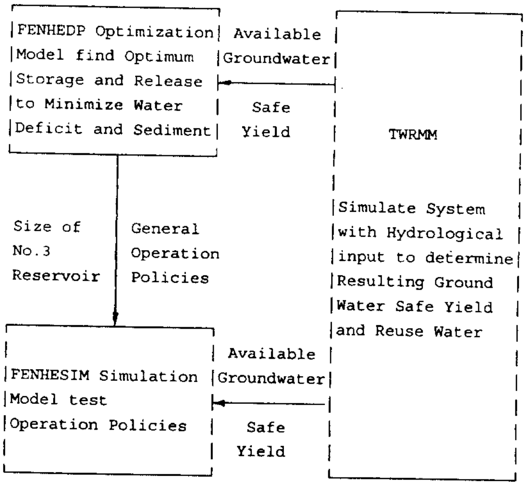


Fig. 5 Fenhe Reservoir Systems Schematic Diagram

Fig.6 General Interconnection of the Models