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Predicting sedimentation process in dam reservoir using mathematical model

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Abstract: Constructing dam in the river path causes hydrodynamic imbalance and consequently all or parts of the sediments are left in the dam. Sedimentation in the reservoir not only reduces the capacity and lifetime of the reservoir, but also causes some problems in opening and closing the deep and semi-deep valves of the dam and increases the level of reservoir, evaporation, and water loss. In this study, in order to predict the sedimentation process in the reservoir of Dez regulating dam, the mathematical model of GATARS3 was applied due to its semi-two-dimensional and quasi-steady property and its ability to simulate sediment transport at the imbalance state. At first, the model was calibrated for an operating period of 28 years using the rating curve of the dam reservoir and then for the future operating periods of the regulatory dam, the rate of sedimentation was predicted. The prediction was done for the operation periods of 40, 50, and 60 years. The results showed that the remaining volume of the reservoir after 60 years of operation (in 2003) was 3.3 million cubic meters which was roughly 76% of the primary volume of the reservoir. In other words, an annual average of about 1.27% of the original volume of the reservoir reduced and the trap efficiency was calculated to be 87%.

Key words: Sedimentation; Regulatory dam; Semi-two-dimensional simulation

1. Introduction

As the sediment enters the reservoir and accumulates there, the effective water storage capacity reduces. This in turn causes the decrease of water storage ability and the loss of adjustment capacity of reservoir overflow. If the sediment is accumulated near the dam body, the lower dischargers and the intake valves might be buried and also their exploitation might be faced with some problems. Moreover, the sediment that reaches the pond output might corrode the turbines and the shield of the lower valves of the reservoir. Reservoir sediment changes depend on factors such as the amount of produced sediments, sediment transport rate, sediment type, sedimentation method, reservoir performance, geometric characteristics of the reservoir, and the changing flow of the river (Frentte and Julien, 1996).

Estimates show that about 0.5% to 1% of the total volume of the dams' reservoirs around the world is lost annually (Atkinson, 1995). The rate of soil erosion in the watersheds in Iran is relatively high which doubles the importance of addressing sedimentation problems in the dams' reservoirs (Palmieri et al., 2003). The average rate of the reduction of reservoirs volume due to sedimentation is estimated to be 0.5 to 7.5 in Iran which is approximately equal to 175 to 250 million cubic meters per year (Tolouee, 2005). Numerical simulation of sedimentation process both in planning and operating phases highly contributes to primary planning and operating management of the dams including the prediction of reservoir sedimentation behavior, structural requirements, setting the executive guidelines of sediment management and optimization of sediment discharge during the operations. During the last two decades a lot of studies have been done to utilize numerical models in investigating reservoirs sedimentation in the rivers and natural streams which have resulted in different conclusions while compared to real conditions. Krishnappan in 1985 compared HEC-6 and MOBED-2 models. Comparison of two predicting models with the collected date showed that predicting ability of MOBED-2 was superior to HEC-6 model and the use of HEC-6 model for determining the manning coefficient and the bed width to the extensive calibration was difficult and time consuming. Fan, 1988 investigated and compared various kinds of software and stated that GSTARS3 model was suitable for solving many engineering problems in semi-two-dimensional and quasi-steady states. Abood et al. (2009) compared some sedimentation models and suggested GSRARS3 and HEC-6 models as successful software in predicting the reservoirs sedimentation pattern. Hassanzade and Khankenedy, (2008) after the calibration of GSTARS3 model via the rating curve of the reservoir of Alavian Dam in Maragheh, Iran made the hydrograph of volume, area, height, and sedimentation in longitudinal and cross sections for the primary bed states and assessed the results of sedimentation analysis for a calibration period of

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nine years and then for a period of 50 years. Ranginkaman et al. (2009) developed a computer model and utilized GSTARS3 as a subprogram and provided the conditions to simulate sedimentation and cleaning the deposits in different conditions of the reservoir utilization with acceptable precision. Numerical models are more affordable than the other ones such as laboratory model. Therefore, in this research the sedimentation process of the reservoir of Dez regulating dam is predicted using semi-two-dimensional model of GSTAR3 which is one of the most practical models used in dam's reservoirs' sedimentation.

2. Introducing gstars3 model and the equations

The GSTARS is a series of Generalized Stream Tube computer models for Alluvial River Simulation developed by the U.S. Bureau of Reclamation for steady and quasi-steady flows. GSTARS 3 further expanded the capabilities of GSTARS 2.1 for cohesive and non-cohesive sediment transport in rivers and reservoirs (Lapin, 1983). The basis for sediment routing computations in GSTARS3 is the conservation of sediment mass. In one-dimensional unsteady flow, the sediment continuity equation can be written as:

$$\frac{\partial Q_s}{\partial x} + \eta \frac{\partial A_d}{\partial t} + \frac{\partial A_s}{\partial t} - q_{lat} = 0 \qquad (1)$$

Where η = volume of sediment in a unit bed layer volume (one minus porosity); A_d = volume of bed sediment per unit length; A_s = volume of sediment in suspension at the cross section per unit length; Q_s = volumetric sediment discharge; and q_{lat} = lateral sediment inflow. A number of assumptions are made to simplify this equation. Firstly, it is assumed that the change in suspended sediment concentration in a cross section is much smaller than the change of the river bed, i.e.:

$$\frac{\partial A_s}{\partial t} << \eta \frac{\partial A_d}{\partial t} \qquad (2)$$

Secondly, during a time step, the parameters in the sediment transport function for a cross section are assumed to remain constant:

$$\frac{\partial Q_s}{\partial t} = 0 \text{ or } \frac{\partial Q_s}{\partial x} = \frac{dQ_s}{dx} \qquad (3)$$

With these assumptions, eq.1 becomes

$$\eta \frac{\partial A_d}{\partial t} + \frac{dQ_s}{dx} = q_{lat} \qquad (4)$$

Which is the governing equation used in GSTARS3 for routing sediments in rivers and streams? By definition, a streamline is a conceptual line to which the velocity vector of the fluid is tangent at each and every point, at each instant in time. Stream tubes are conceptual tubes whose walls are defined by streamlines. The discharge of water is constant along a stream tube because no fluid can cross the stream tube boundaries. Therefore, the variation of the velocity along a stream tube is inversely proportional to the stream tube area. Fig. 1 illustrates the basic concept of stream tubes used in GSTARS3.

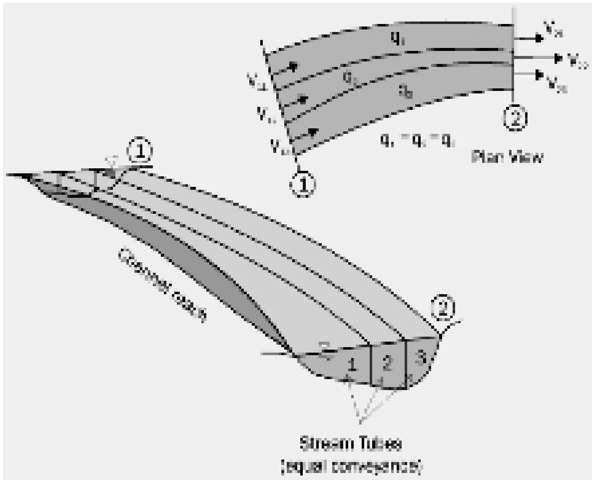

Fig 1: Schematic representation illustrating the use of stream tubes by GSTARS3

3. Materials and methods

Dez regulating dam is constructed on the Dez River 2 km upstream the third bridge in Dezful in Khuzestan Province. The dam is at latitude 32 °, 2 4 ′, 3 9 ″ N and 48 °, 2 5 ′, 2 1 ″ E. It has been planned and constructed in order to regulate the output water of the Dez reservoir dam (located upstream of the regulatory dam) and to supply the water that enters the irrigation network in an area of 125000 hectare and to flow out the flood equal to 6000 m^3/s. the dam was utilized since 1972 in order to supply the water required for 20000 hectare of the lands in the experimental irrigation project of Dez. The technical features of the dam are as the following:

Type of dam: regulatory-concrete gravity, dam length: 126 m, Lake area: 3.31 km^2, crest length: 126 m, height from the foundation: 25.8 m, reservoir capacity: 14 million cubic meters.

Data relating to the method of operation of the reservoir, hydrologic data, discharge data of the inflow sediment to the reservoir, input sediment grading, and sediment grading of the bed materials were collected. Then the collected data were introduced to the model in two parts including hydraulic data and the sedimentation data. In order to introduce the dam reservoir topography to the model it was necessary to have access to different sections of the dam. Therefore the hydrograph related to 1973 was used. In order to calibrate roughness coefficient, the level of upstream reservoir water in upstream hydrometer station was compared to the water level resulting from the model operation. After the model calibration, the roughness coefficient of 0.035 (with the assumption of constant roughness in the stream bed and its coasts in all sections) was suggested. With respect to the flow-sediment discharge curve (Fig. 2) and its fit the sediment discharge equation was calculated as the following:

$$Q_s = 0.3621(Q_w)^{1.174} \quad (5)$$

In this equation, Q_s is the sediment discharge and Q_w is the water discharge. According to the samples which are taken, the grading of the input sediment to the reservoir is displayed in Fig.3.

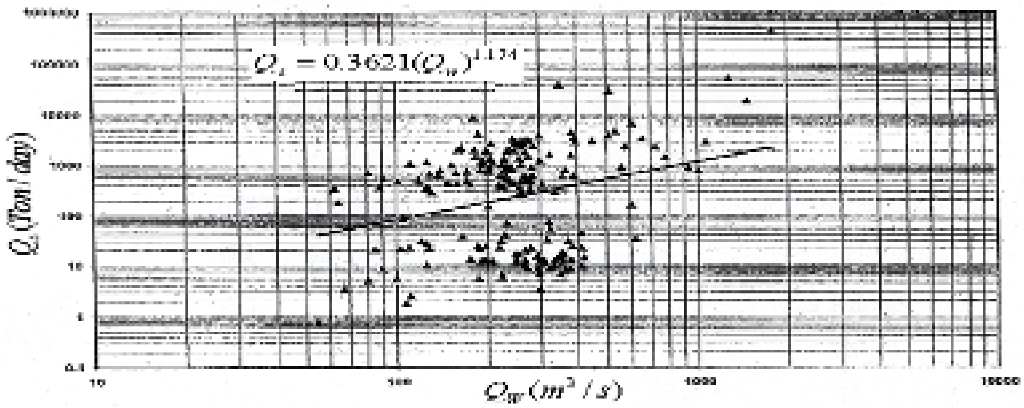

Fig. 2: The curve of flow-sediment discharge in Dez regulatory dam

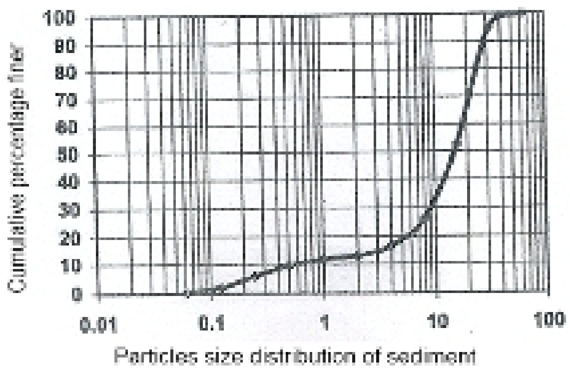

Fig. 3: Grading curve of the input sediments to the dam reservoir

After preparing the data and entering them into a text file, the model was implemented. Three hydrographic sections were needed for calibration and verification (one as the primary section and two sections for calibration and verification). In this research the hydrographic sections of 1973 were introduced to the model as the primary sections and the hydrograph of 1987 was used for the model calibration. In order to examine the verification conditions, four sections of the 1987 sections were used and after the calibration processes, the change of parameters at calibration phase was repeated as a cycle for verification. The cycle stops when the value of the parameters remains unchanged compared to the previous calibration stage. In order to increase the accuracy of the output, the calibration operation was performed for the coefficients of the model which owned the default values. In sedimentation discussion, sediment transport function is the factor that has the highest effect on the results. The standard Error (STE) for each sediment transport function was calculated via the following formula and mentioned in Table 1:

$$STE = \left(\frac{1}{n-1}\sum_{n=1}^{n}(X_{Oi} - X_{Ti})^2\right)^{0.5}$$

$$\eta \frac{\partial A_d}{\partial t} + \frac{dQ_s}{dx} = q_{lat} \quad (6)$$

Where, X_{Oi} and X_{Ti} are respectively the experimental and theoretical values of hydrologic data and n is the number of statistical years [10]. According to this table, Yang equation (1979) has the lowest error so it was used for calibration processes.

Table 1: Comparison of error rates of sediment transport functions (Yang and Simoes, 2002)

sediment transport equation	STE
Laursen (1958)	2.7
Laursen modified by Madden (1993)	2.13
Toffaleti (1969)	2.98
Engelund and Hansen (1972)	7.52
Ackers and White (1973)	3.54
Ackers and White (HR Wallingford, 1990)	5.71
Yang (1973) + Yang (1984)	2.48
Yang (1979) + Yang (1984)	1.08
Parker (1990)	1.98
DuBoys (1879)	1.73
Meyer-Peter and Müller (1948)	2.32
Ashida and Michiue (1972)	2.56
Tsinghua University (IRTCES, 1985)	2.28

4. Profile changes of the dez river bed

The Dez River enters the plain at the downstream of the reservoir dam in Dast Meshan Station (upstream border of the studied area). The length of the studied area from Dast Meshan station to the regulatory dam with regard to the survey in 1999 is equal to 12 km. The beginning of the lake of the regulatory dam is located at Cham Galak Village and 6.6 km away from the regulatory dam axis. The river bed has a lot of ups and downs in some sections of the river due to little depth of flow and growth of the reeds and consequently the slow flow in the vicinity of the reeds and their effect has been considered in simulating the river using the roughness and bed resistance coefficient within the above areas. The increase of water level in the regulatory dam and its effect on the upstream area has led to the deposition of a lot of sediments in the reservoir, so that in most cross sections the sedimentation is observed. Therefore, according to the results of the model implementation, the optimal and planned utilization of the regulatory dam can have a significant effect in reducing the sedimentation in the reservoir. The longitudinal profile of the Dez River bed in the studied area after different periods of operation (28, 50, 40, and 60 years) was drawn via implementing Gtars3 model. In Fig.4, the longitudinal profile of the river bed is shown after 60 years of operation.

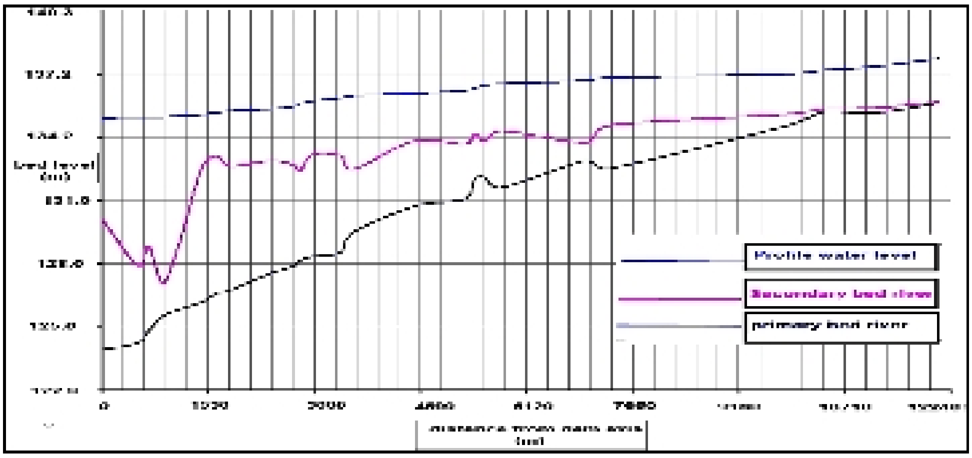

Fig. 4: The longitudinal profile of the river bed resulting from the implementation of the model after 60 years of Dez dam operation

5. Reservoir volume changes over time

Predicting the reservoir volume in the coming years is highly significant for planning the water resources. Moreover, the reservoir sedimentation position affects the preservation and recovery strategies of the reservoir storage capacity. In order to predict the reservoir volume in the next years, since the Gstar3 model does not provide the amounts of volume corresponding to different levels of the reservoir (H) as the output for the user, in this research in order to calculate the area and the volume of the reservoir at different levels, the reservoir topography with the mesh of 1000 X 500 was drawn using the output data of Gstars 3 model and by means of SUPER 7 software. Then, the reservoir area and volume were calculated using the present topography at different levels. The reservoir volume changes at different time periods were estimated and the diagram was drawn by using the results of the above calculations (Fig. 5).

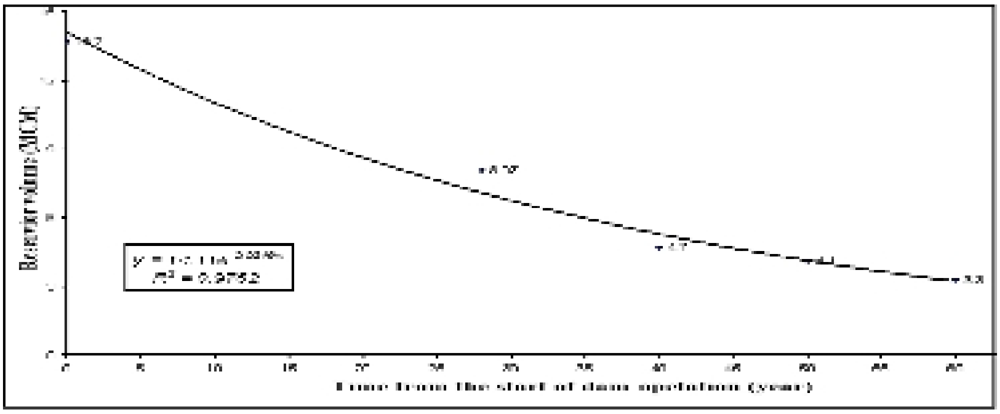

Fig.5: The relationship between the reservoir volume changes and the time resulting from the implementation of GSTA3 model

Moreover, the relationship between the reduction of reservoir volume and time was obtained through the corresponding diagram:

$$V = 14.11 \times e^{(-0.0246T)}, \qquad R^2 = 0.9762 \quad (7)$$

Where, T is the time since the start of dam operation (year) and V is the reservoir volume in million cubic meter (MCM). The review of the reservoir volume changes and the sediments accumulation in the reservoir indicates those 60 years after the beginning of the regulatory dam operation, the volume of the sediments deposited the reservoir is 76% of the primary volume of the reservoir. In other words, an average of about 1.27 of the initial volume of the reservoir has reduced annually due to the sediments accumulation.

6. Volume – height curves

In this section, the volume – height curves are presented. The curves are important due to the reservoir operation issues. With respect to the results of implementing Gstars 3 model and the conducted hydrograph in 1999 (28 years after the reservoir operation) and the obtained geometry, the curve of volume-height was drawn using Surfer program. The primary volume – height curves of the reservoir resulting from implementing Gstars 3 model for the beginning of operation and the time periods of 28, 40, 50, and 60 years are shown in Fig.6.

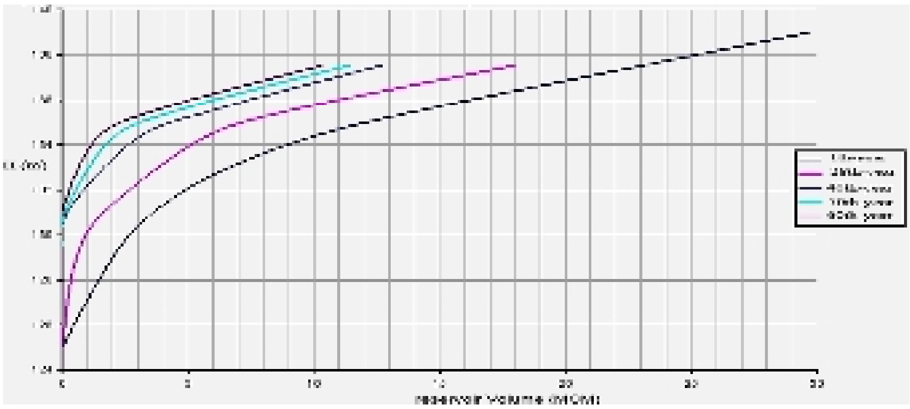

Fig.6: Volume – height curve for different simulation periods

7. Conclusion

In this research, in order to predict the sedimentation process in the reservoir of Dez regulatory dam, the semi-two-dimensional model of GSARS3 was used. After the model calibration through the rating curve of the dam reservoir, the sedimentation at longitudinal section was drawn. In each calibration stage, the coefficients were determined in such a way that the error function of STE would be minimized. According to the prediction of the model it can be stated that in 2032 about 76% of the primary volume of the reservoir will be filled with sediments. In other words, an average of about 1.27 of the initial volume of the reservoir reduces annually due to the sediments accumulation. Moreover, an equation was extracted and presented to determine the reduction of the reservoir volume over the time.

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