African Journal of Agricultural Research Vol. 5 (1), pp. 060-069, 4 January, 2010
Available online at http://www.academicjournals.org/AJAR
DOI: 10.5897/AJAR09.472
ISSN 1991-637X © 2010 Academic Journals

Full Length Research Paper

Evaluation of variation of useful storage of reservoir in stream dams by GSTARS3 software

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Accepted 2 October, 2009

Stream dams are small dams. If the conditions of site are not suitable for construction of reservoir dams, stream dams will be constructed. These dams have small reservoirs. These dams are without gate or these are controlled by gates. The major problem of stream dams is sedimentation special in rivers with high sediment load. In gated stream dams, flushing is accomplished by opening of the gates in flood condition. Construction of physical model is very difficult for evaluation of efficiency of flushing in removal sediment from reservoir of stream dam. Also the cost of construction of physical model is very high. Development of mathematical models is essential for modeling of successive processes of sedimentation and flushing in useful lifetime of stream dams. Because of variation of boundary conditions in successive processes of sedimentation and flushing of gated stream dams, Available mathematical models can not model continuously these processes at total of yield period. In this research, the long term sedimentation and flushing process will be simulated by development of a mathematical model. Modified mathematical model can simulate successive processes of sedimentation and flushing in useful lifetime of stream dams for different conditions of use of reservoir. The time and cost of simulation by modified mathematical model is very low. Also accuracy of this model is acceptable for simulation. In this research, the case study is successive stream dams on the Dez River in Iran (Dez1 Dam, Dez2 Dam and Dez3 dam) for evaluation of efficiency of modified mathematical model.

Key words: The Dez river, stream dam, GSTARS3, flushing, sedimentation.

INTRODUCTION

Because sedimentation decreases volume of reservoir of dam, conservation from reservoir, retrieval of useful storage of reservoir and increasing useful life time of reservoir are very important problems in design and construction of dams. A great number of researches are accomplished for studying of sedimentation and flushing action in dams. Several formulas and theories were developed by developing of mathematical models and different soft wares in special conditions for calculation of volume of sedimentation, erosion and sediment transport.

Many researchers studied sedimentation in reservoir and effects of flushing. But they paid attention to theoretical aspects of this subject. They applied numerical models and stochastic methods for their researches. For example, Salas et al. (1999) made used of Monte Carlo simulation and Latin hypercube sampling for quantify the uncertainty of annual reservoir sedimentation and accumulated reservoir sedimentation through time. Their case study was the Kenny Reservoir at the White River Basin in Colorado. Fan et al. (1992a, 1992b) applied hydraulic models for studying sediment routing during floods, sediment flushing during floods, emptying and flushing, and density current venting. They considered several dams and rivers in China (Sanmenxia, Guanting, Shanyiujiang, and Liujiaxia reservoirs, as well as the Shanshenggorig barrage and Xijin hydropower station). Chaudhuri (2006) evaluated different methods for preventing from entrance of sediment to Maithon Reservoir in India. He considered different methods for removal of sediment in this reservoir too. His aim was increasing life of Maithon Reservoir. Wu et al. (2007) studied on the reservoir sedimentation processes in response to changes in incoming flow at the upstream and changes in the pool

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level at the downstream for Sanmenxia Reservoir, which is located on the middle reach of the Yellow River in China.

In this research, a mathematical model was modified by adding several subroutines to it. Modified model can simulate sedimentation and flushing in the reservoir of dams continuously and can draw variation of useful storage of reservoir at the end of each period of sedimentation and flushing action.

RESEARCH METHODOLOGY

The major aim of construction of stream dams is production hydro-electricity energy. For production of hydroelectricity energy, several stream dams must be constructed on the river. Successive stream dams can not reserve a great volume of water in reservoir. The aim of design and construction of hydropower plant is production of design peak hydroelectricity energy. The successive hydropower plants are a continuous system. This continuous system can prepare necessary hydroelectricity energy in the peak hours of consumption of electricity energy. Because of difference of elevation between upstream and downstream of stream dam, potential energy of the upstream of the stream dam convert to kinematics energy of the downstream of the stream dam. Kinematics energy spins turbine and produces electricity energy. Then water returns to river without variation of its discharge. Stream dams without gate or gated stream dams have small reservoirs and they can reserve a little water in their reservoirs. Because of their small reservoirs and their low heights, sedimentation is the most important problem for them. If sediment load of river is very much, reservoir sedimentation would very important (Freedman, 2007). In design of stream dams, it is necessary attention to sedimentation problem. If this subject is not considered, sediment can fill reservoir very rapidly and useful lifetime of reservoir decreases. Also design without considering sedimentation has not any finance rationalization. Fine sediment can arrive to waterways of hydropower plant and erode pieces that contact to water. This subject causes reduction of their useful lifetime (Jiahua et al., 1992; Nozaki, 1990). Therefore long term simulation of sedimentation is an important part of design studies of stream dams. The major problem of sedimentation simulation is flushing concept. Determination of suitable discharge for flushing in operation period of stream dam, the efficiency of flushing for retrieval of useful storage of reservoir, determination of effect of sediment grain size, sediment discharge, dry period and wet period must be considered for design of different aspects of flushing procedure. Although physical models are more exact than mathematical models but their cost and their limitation are more than mathematical models. Therefore for primary studies, mathematical models are suitable.

Comparison between mathematical models and selection suitable model

Sediment transport in rivers and reservoirs and erosion and sedimentation are very complex problems in river engineering. Available models make used of assumptions for simplified of these problems. Because some assumptions are based on idealization of experimental conditions, they are not possible. In the other hand, it is need to a large number of data for access to suitable theory in real conditions. Of course these data are utilizable for special conditions and special locals. For using of empirical results and mathematical models of other researchers, available conditions must similar to conditions that these formulas and theories are extracted based on them. Developed models were established by using up a great amount of data. These models are rather suitable. For using of them at available conditions, they have to be calibrated.

In addition to a selected mathematical model must simple, it can consider effective parameters in order to accessibility to a suitable design. If data are not exact, using of a mathematical model that needs to a great amount of data will not suitable. Recognition of principles of available models and difference between their practical conditions is necessary for a designer. In this research a suitable model will be selected by comparison between available models for sedimentation and flushing procedure.

Classification of mathematical models

Mathematical models are classified spatially to four classes (1-D, 2-D, 3-D and quasi 2-D). Quasi 2 dimensional models classified to three classes (Strip model, Stream tube model and composite model). Although 3 dimensional models can analysis hydraulic conditions of river exactly but these models need to a great amount of 3 dimensional data. The time and cost of preparation of these data is very high. These data must be prepared only for special projects that need to very high accuracy. Flow 3d, Mike3, CFX and SMS9 are 3 dimensional models. These models make used of perfect form of flow equations for determination of water surface elevation and sediment transport. Because of the solution of perfect form of flow equations increases time of solution, 3 dimensional models can not simulate long term currents. If available data are enough, 3 dimensional models will exact otherwise accuracy of these models will similar to accuracy of 1-D, 2-D and quasi 2-D models (Olsen, 1999; ICOLD, 2004).

Often 1 dimensional model is applied for simulation problems of rivers. The most of models are 1-D models in river engineering. These models can simulate long term currents in rivers. But accuracy of 1-D models is very lower than accuracy of 2-D and 3-D models. These models need to a few data for calibration. The time of solution is very low in these models. Numerical stability of these models is more than numerical stability of 2-D and 3-D models. But 1-D models can not show lateral variations of hydraulic conditions of current and pattern of lateral sedimentation in crass sections of rivers. Also these models can not simulate lateral erosion. For using of advantages of 1-D models and modeling of lateral variations of hydraulic conditions, quasi 2-D models are suitable (Yang et al., 2003). The accuracy of 1-D and quasi 2-D models is sufficient for evaluation of sedimentation and flushing problems in reservoir of dams. For example the possibility of flushing and its efficiency can be modeled by these models. Results of these models can help to decision of designer (ICOLD, 2004). Sediment transport models divided to steady or unsteady models, coupled or uncoupled models, uniform or no uniform models and equilibrium or no equilibrium models. These classifications of models were explained by researchers (Yang, 2006; Yang et al., 2003, 2000; ICOLD, 2004).

Sediment transport soft wares

For simulation of sediment transport, a number of models were developed. Some models were developed for a special project. These models can be applied for similar projects to this project. They can not calibrate for rivers with different conditions. But a number of models were established based on correctly theoretical principles. These models need to a great amount of data for calibration. On the other hand a number of models are very simple and accuracy of their results is very low. A sediment transport model must have follow characteristics (Yang, 2006):

- The assumptions of mathematical equations of model must have conformity with considered river conditions.
- These models should useable for constant bed and deformable

bed.
- These models should useable for supercritical flow, sub critical flow, critical flow and mixed flow.
- These models should simulate longitude and lateral variations of hydraulics conditions and sediment transport.
- Sedimentation and sediment transport are modeled based on sediment grain size curve. By using of this curve, armoring, stabilization of bed form and simulation of long term variations of sedimentation and hydraulic conditions can be simulated.
- Ability of simulation and prediction of shape of channels, depth variation and lateral variation of cross sections
- Ability of simulation sediment transport at equilibrium conditions and no equilibrium conditions
- These models can consider the kind of material of bank of channel, stability of bank and upper bound of erosion of bank.
- Model do not need a great amount of data that user can not prepare them.

The most famous models for simulation of sediment transport are:

Mike 11, Wendy (Saflow, Seflow, Susflow and Odirmo) models, NETSTARTS, FLDSTARS, HEC-6, GSTARS 2.1 and GSTARS 3. International research institute and Fan et al. accomplished a perfect comparison between abilities and practicability of 8 sediment transport models. These 8 models are including CHARIMA, FLUVIAL-12, HEC-6, TABS2, MEANDER, USGS, GSTARS and D-O-T.

The results of this comparison are shown in Table 1.

CHARIMA, FLUVIAL-12, MEANDER and D-O-T are academic models while HEC-6, TABS2, USGS and GSTARS developed by federal governing of U.S.A for practical projects. The results of this comparison are (Fan, 1988; National Research Council., 1983):

- Although only 3-D models can simulate hydraulic conditions and sediment transport of rivers exactly, but often 2-D and 3-D models are applied for simulation in small parts of rivers that their hydraulic conditions are very complex. By attention to shortage of field data, 1-D models are suitable for long term current simulation. If simulation of lateral variations of bed of river is necessary, quasi 2-D models must be applied.
- Because of variation of hydrologic conditions, hydraulic conditions are unsteady special for flood conditions. For non flood conditions, time divided to small time steps and discharge hydrograph convert to histogram.
- Uncoupled finite difference method is usual method for solving sediment transport equation.
- The results of sediment transport model are sensitive to selected sediment transport equation. For selection a suitable equation, it must be considered theory and application conditions of sediment transport equation.
- In the most of sediment transport models, width of river is constant. In the other word bank of river is not eroded by flow. This assumption is incorrect for alluvial rivers. At resulting, these models can not model sediment transport correctly.
- The theories of GSTAR3 model is stream tube theory and theory of minimum power of current. This model makes used of energy equation and momentum equation for determination of water surface elevation. Also this model considers sediment grain size, forming of armor layer, variations of width of river, stability of slope of bank of river and soon for sediment transport. This model is a quasi 2-D and quasi unsteady model. GSTARS3 model does not need to a great amount of data for calibration. GSTARS3 model is a new model that calculates water surface elevation and sediment transport in rivers with deformable bed. Also this model can simulate sedimentation and flushing procedure. Yang and et al. developed this model in USBR (Yang et al., 2003).

Necessary data for GSTARS3 model

Sediment transport models need to basic information for simulation. A number of basic information is geometry of cross sections, Manning's coefficient, sediment grain size curve, fine sediment characteristics and yield regime.

Basic parameters classified to three classes:

1) Geometric and hydrologic characteristics of river
2) Discharge of sediment
3) Grain size of sediment and characteristics of sediment

Geometric characteristics of river will be prepared by survey. For calibration and validation of model, at least hydrographic action must accomplish in three periods. Often relation between discharge of flow and sediment load is an exponential relation. This exponential relation is prepared by SCS method and data of hydrometric stations.

This relation is known as discharge- sediment discharge equation and it is applied for determination of sediment load at different time steps (daily period, monthly period and yearly period). Also this equation can be prepared by different mathematical methods or optimization procedure. For determination of sediment grain size curve, it makes used of available data, sampling from bed load and suspended load.

Because of stochastic characteristics of discharge of river and non predictability of floods, time periods of sedimentation and flushing is determined by trial-error method. For this purpose, reservoir is simulated by different strategies in its lifetime period. The best strategy is selected based on results of reservoir simulation for different strategies. Also effects of different parameters on selected design must be evaluated.

Based on yield regime, considered strategies are:

1) Using of an alarm flood system: This system alarms to operator before arriving of flood to reservoir. In this state, flushing is accomplished in flood period. Sedimentation occurs in non flood period.
2) In this state, if arriving instantaneous discharge to reservoir is more than a distinguished limit, the gates of stream dams will open rapidly and flushing will start. After arriving instantaneous discharge to reservoir decreases to less than distinguished limit, the gates of stream dams will close and sedimentation will start. By construction a hydrometric station at upstream of reservoir, this method becomes more practical than previous method.

Modification of GSTARS3 model

Because the most of models simulate flushing and sedimentation discontinuously, cross sections of river and boundary conditions must modify based on results of previous state for calculations of new state. By attention to great number of cross sections and simulation periods, this modification increases time of running of model very much. In this research GSTARS3 model was modified by researchers. Several subroutines were added to model. By adding these subroutines, model can distinguish suitable time for flushing action. Also these subroutines can modify geometry of cross sections of river and boundary conditions automatically for successive periods of sedimentation and flushing. In the other word, these subroutines convert model to a continuous model. This model evaluates efficiency flushing for retrieval useful storage of reservoir. Modified GSTARS3 model can preprocess results of model. This model shows cross sections of river and longitude profile of river graphically also calculates the volume of useful storage of reservoir. By these modifications, results of model can be evaluated by user very rapidly. If hydraulic and hydrologic conditions are suitable in the upstream of reservoir, the volume of useful storage of reservoir

Table 1. Comparison between sediment transport models (Fan, 1988).

GSTARS2.1/ GSTARS3	D-O-T	USGS	Meander	TABS-2	HEC-6	Fluvial-12	CHARIMA	Model
Discretization and formulation:								
N/Y	N/Y	Y/Y	N/Y	Y/Y	N/Y	Y/Y	Y/Y	Unsteady flow/Stepped hydrograph
Y/Y	Y/Y	N/N	N/N	N/N	Y/N	Y/Y	Y/N	One dimensional/quasi two dimensional
N/Y	N/N	Y/Y	Y/Y	Y/Y	N/N	N/N	N/N	Two dimensional/depth-average flow
Y/Y	Y/Y	Y/N	Y/N	Y/N	Y/N	Y/Y	Y/N	Deformable bed/banks
Y	Y	N	Y	Y	Y	Y	Y	Graded sediment load
Y	Y	Y	Y	Y	Y	Y	Y	Non-uniform grid
Y	N	N	N	N	Y	N	Y	Variable time stepping
Numerical solution scheme:								
Y	Y	N	N	N	Y	Y	N	Standard step method
Y	Y	Y	Y	N	Y	N	Y	Finite difference
N	N	N	N	N	N	N	N	Finite element
Modeling capabilities:								
Y	Y	Y	Y	Y	Y	Y	Y	Upstream water and sediment hydrographs
Y	Y	Y	Y	Y	Y	Y	Y	Downstream stage specification
N	N	N	N	Y	N	N	N	Flood plain sedimentation
N/Y	N/Y	N/Y	N/N	Y/N	N/Y	Y/N	Y/N	Suspended/total sediment transport
Y	N	N	Y	N	Y	Y	Y	Bed load transport
Y	N	Y	N	Y	Y	N	N	Cohesive sediments
Y	Y	N	N	N	Y	Y	Y	Bed armoring
Y	Y	N	N	N	Y	Y	Y	Hydraulic sorting of substrate material
Y	Y	N	N	N	N	Y	N	Fluvial erosion of stream banks
N	Y	N	N	N	N	N	N	Bank mass failure under gravity
Y/Y	Y/Y	N/N	N/N	Y/Y	Y/N	Y/N	Y/N	Straight/irregular non-prismatic reaches
N/N	N/N	N/N	N/N	Y/Y	Y/N	Y/N	Y/Y	Branched/ looped channel network
Y	Y	N	Y	Y	N	Y	N	Channel beds
N	N	Y	N	N	N	N	N	Meandering belts
Y	Y	Y	Y	Y	Y	Y	Y	Rivers
N	N	N	N	Y	N	N	N	Bridge crossings
Y	N	N	N	N	Y	Y	N	Reservoirs
User support:								
Y	Y	Y	Y	Y	Y	Y	Y	Model documentation
Y/N	N/N	Y/N	N/N	Y/N	Y/Y	Y/N	N/N	User guide/hot-line support

useful storage of reservoir become a constant volume after several years. In the other word state of reservoir become an equilibrium state. For observation of this situation, a subroutine was added to GSTAR3 model that draws diagram of useful storage of reservoir at

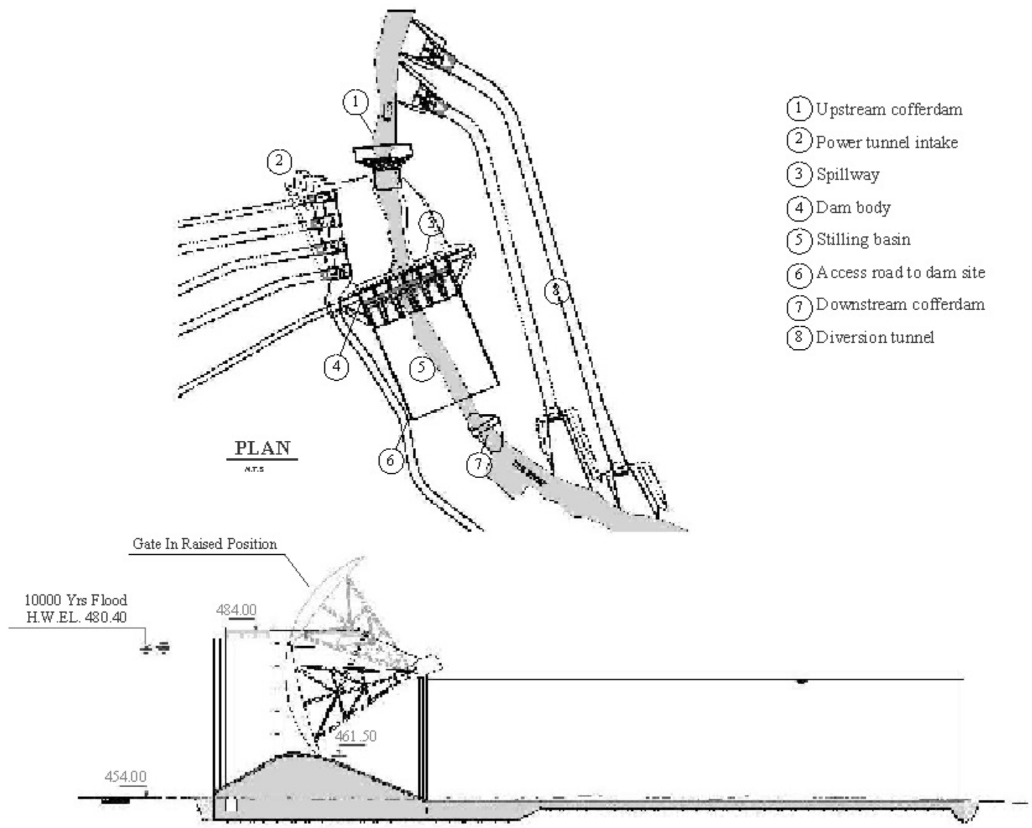

Figure 1. General characteristics of the Dez2 dam.

the end of each period of modeling.

For evaluation of modified model in a practical project, the successive stream dams (Dez1, Dez2 and Dez3) are considered.

These stream dams will construct on the Dez River for production of hydroelectricity energy.

CASE STUDY

For production of hydroelectricity energy, the successive Dez stream dams makes used of difference of elevation between reservoir of the Dez dam and hydropower plant of the Bakteari dam. This difference of elevation is175 m. the major part of discharge that passes from hydropower plant of the successive Dez stream dams is outflow from hydropower plant of the Bakteari dam. Other part of discharge that passes from hydropower plant of the successive Dez stream dams is prepared by reservation and daily regulation of flows of the Sezar River and the Dez River in the reservoir of the successive Dez stream dams. For example general characteristics of the Dez2 dam are shown in Figure 1; also the downstream and upstream of the Dez dam are shown in Figures 2 and 3 respectively.

The total volume of reservoir of the Dez1 dam, the Dez2 dam and the Dez3 dam is 14, 5 and 12 MCM respectively. Yearly sediment load is 16.5 MCM that arrives to reservoir of the successive Dez stream dams (Dezab Consulting Engineer, 2005). The concentration of sediment is very low in non flood periods. Therefore a great of volume of sediment arrives to reservoir of the successive Dez stream dams in flood periods. For prevention of sedimentation in flood periods, the large gated spillways will be put on the body of the successive Dez stream dams. The width of these spillways is equal to width of river. The height of sector gates is more than half of height of dam. After starting of flood, these gates will open and flushing action will start. In this situation, flow is similar to an open channel flow. This flow will be conducted from crest of spillway toward the downstream of dam. The flood and almost the total of water in reservoir will be vacated by flushing.

RESULTS

Hydraulic conditions of flushing are similar to hydraulic conditions of river flow. The geometry of cross sections of river was exploited by using of topographic maps with scale 1:2000. The discharge of inflow to reservoir was extracted by discharge data of Talezang hydrometric station in the upstream of reservoir. Annual discharge of inflows at Talezang hydrometric station is shown in Figure 4 from 1955 - 2001. Discharge- sediment discharge equation was prepared by sediment data of Talezang hydrometric station and non linear optimization method. This equation was calibrated by data of deposited sediment in reservoir of the Dez dam. This equation is shown at follow:

$$Q_{sr} = 0.028 Q_w^{2.21} \quad Q_w \leq 505 CMS \tag{1}$$

$$Q_{sr} = 0.04 Q_w^{2.19} \quad Q_w \geq 505 CMS \tag{2}$$

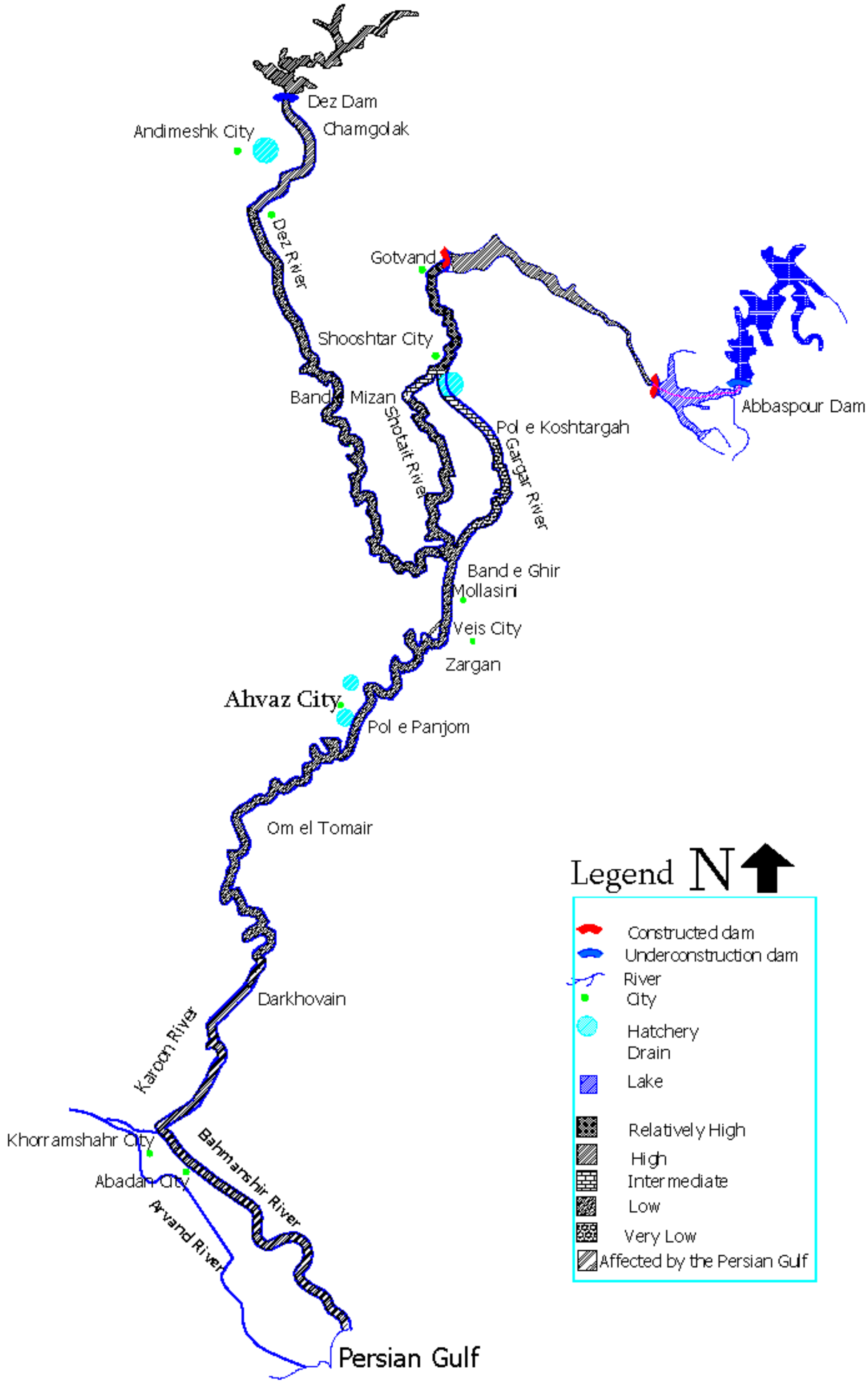

Figure 2. The map of downstream of the Dez dam.

Where:

Q_{sr}: The total sediment load of the Dez River in regulated condition (Tons/day)

Q_w: The discharge of the Dez River in regulated condition (CMS)

Because of lacking of sediment data in the Dez River and

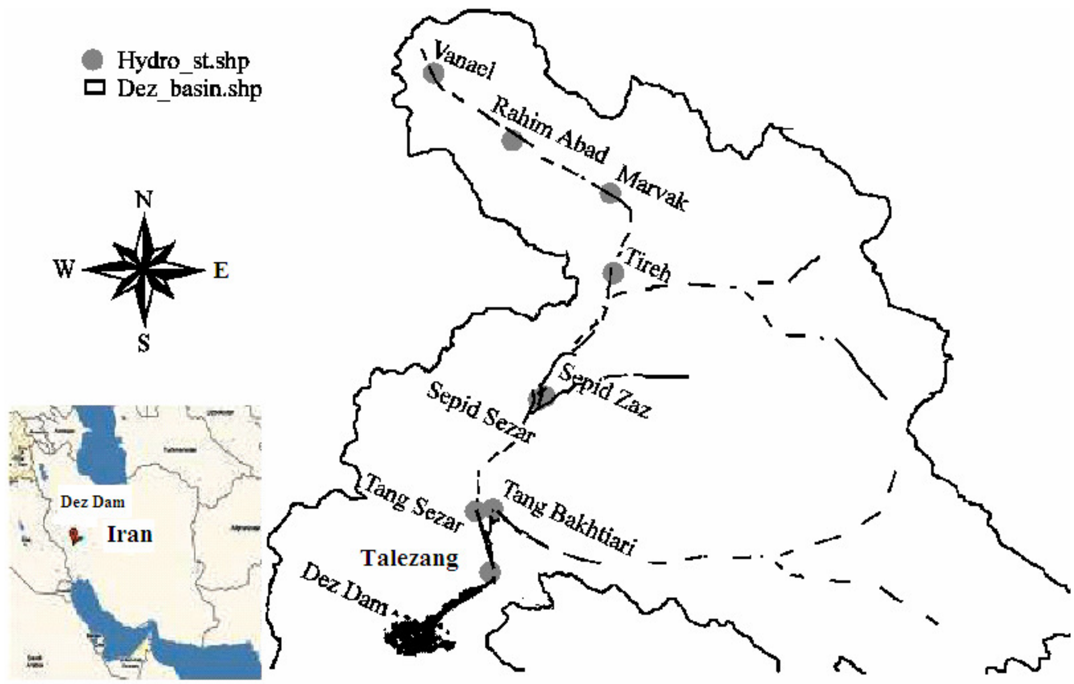

Figure 3. The map of upstream of the Dez dam and its location in Iran.

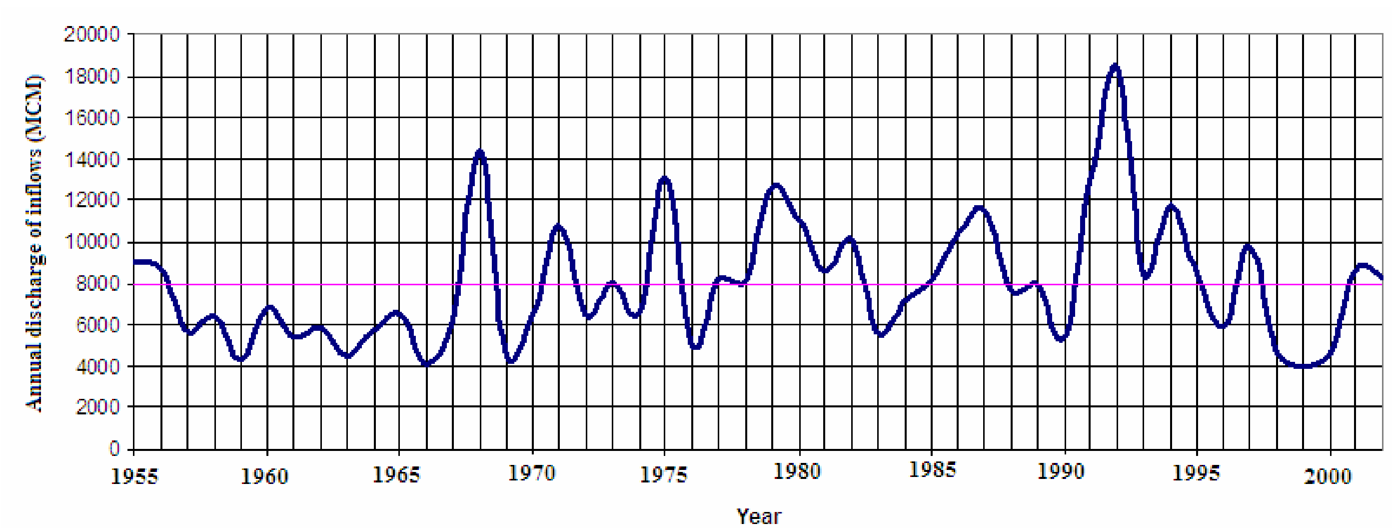

Figure 4. Annual discharge of inflows at Talezang hydrometric station from 1955 - 2001.

armoring of the bed river, it made used of sediment grain size of deposited sediment in reservoir of the Dez dam for determination of sediment grain size curve. For simulation of long term reservoir operation, reservoir characteristics at the end of each period are initial conditions of future period in different sedimentation and flushing periods.

For determination of optimum discharge of flushing at the lifetime of reservoir, three states were considered for running of model:

1) By assumption of existence an alarm flood system, daily discharge for sedimentation and recorded hourly flood hydrograph for flushing can be considered.
2) If daily discharge is more than 1000 CMS, flushing will start.
3) If daily discharge is more than 1200 CMS, flushing will start. 1000 CMS and 1200 CMS were selected based on limitation of hydropower plant. The results of three states are shown in Figure 5 for the Dez1 dam. This figure shows that if state 2 is considered for flushing action,

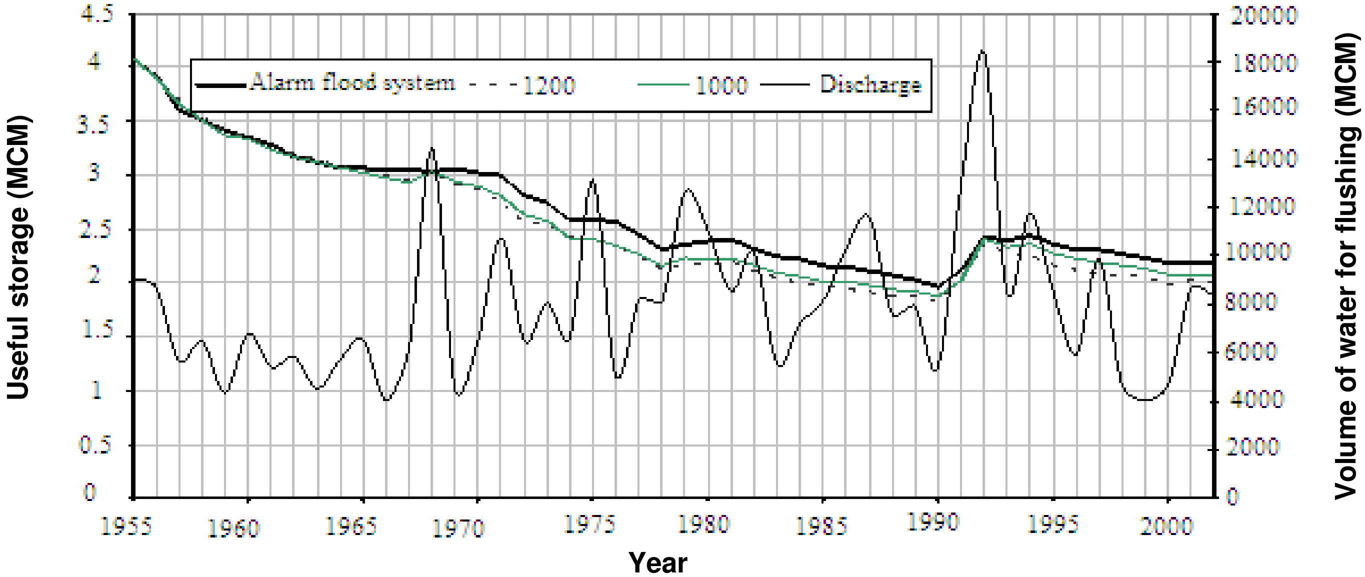

Figure 5. The variations of useful storage of reservoir of the Dez1 dam for different flushing scenarios in 48 years (Simulated by modified GSTARS3 model).

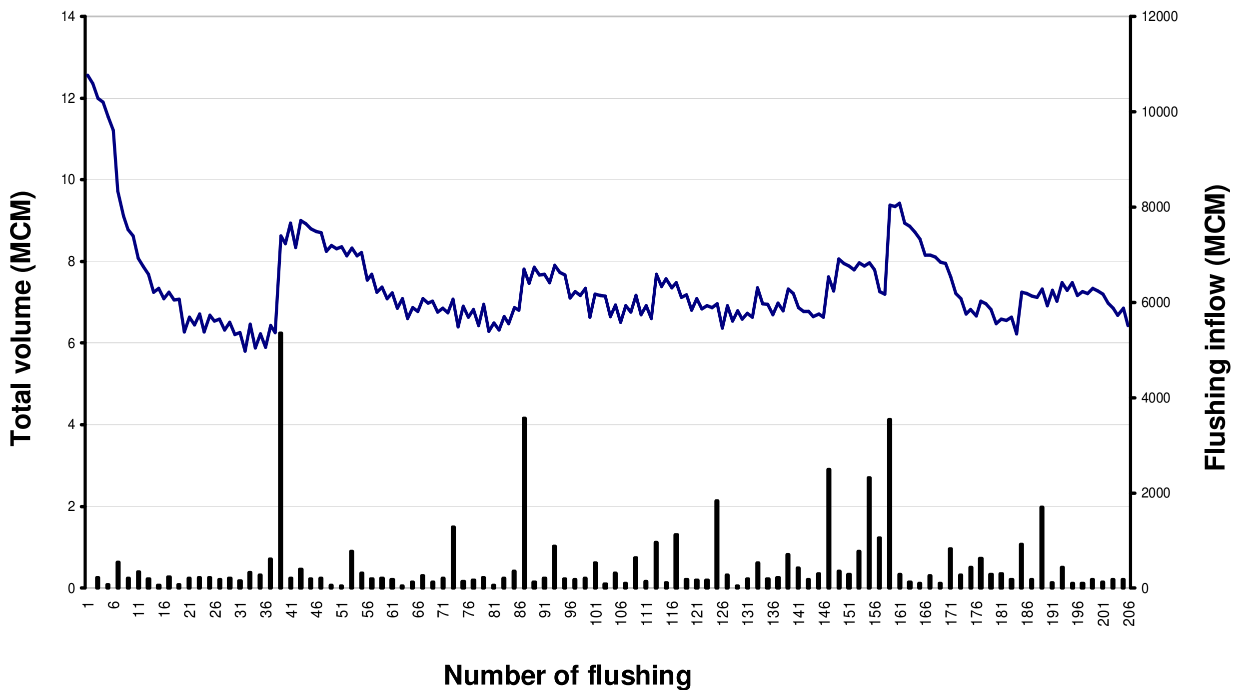

Figure 6. Variation of total volume of reservoir for actual sediment yield.

remainder useful storage will sufficient and cost of flushing will optimum. For validation of modified model in state 2, two cases were considered.

Case1: Calculation of variation of total volume of reservoir for actual sediment yield.

Case 2: Calculation of variation of total volume of reservoir for 1.2 times actual sediment yield.

The results of two cases are shown in Figures 6 and 7. Horizontal axis expresses the number of flushing action from 1955 - 2001.

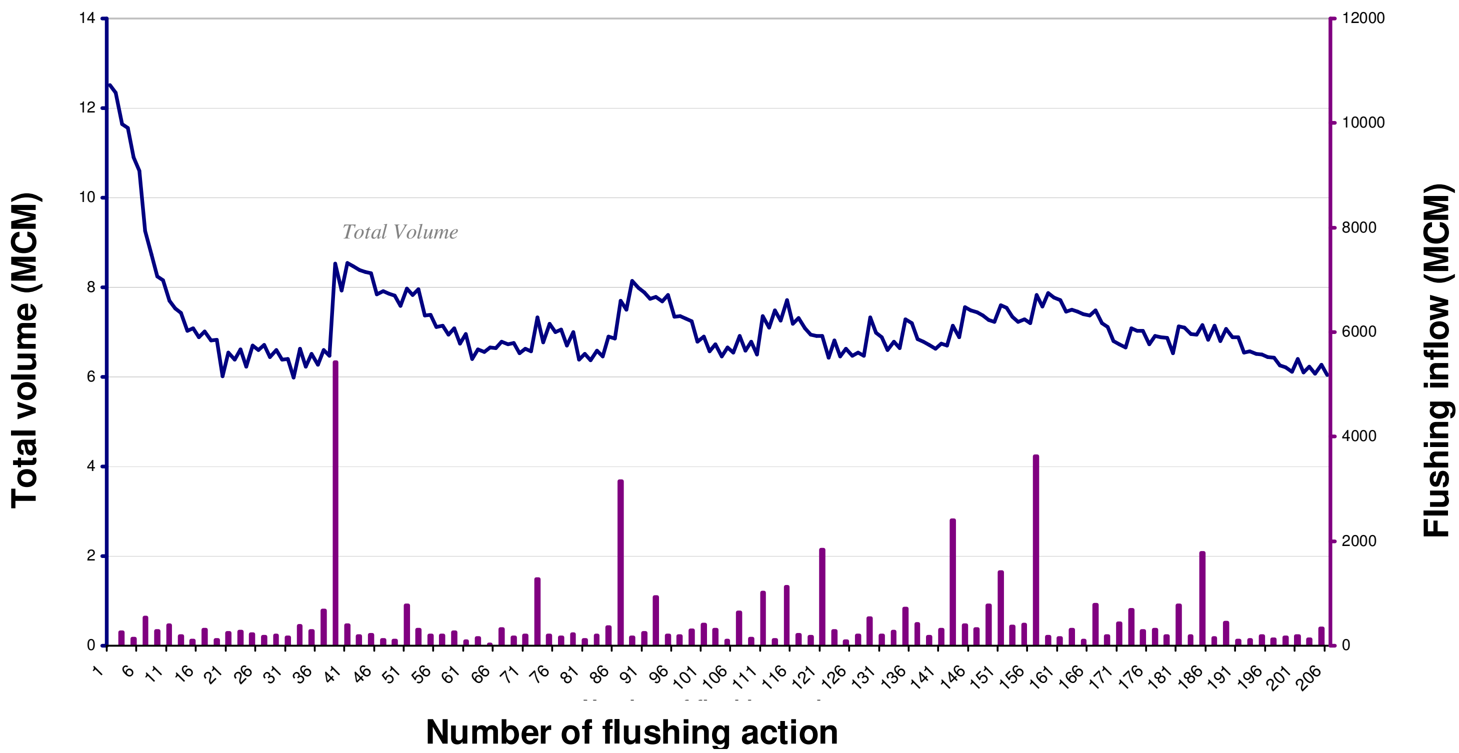

Figure 7. Variation of total volume of reservoir for 1.2 times actual sediment yield.

DISCUSSION

Mathematical models that simulate sedimentation and flushing can help to designer. These aids include of reduction of studying time and costs and increasing of accuracy of research. The total of cross sections of river and longitude profile can be drawn by modified GSTARS3 model. This model can calculate exactly dead storage and useful storage of reservoir at the end of each period of sedimentation and flushing. Calculation of dead storage and useful storage of reservoir is very important in projects of preparation of hydroelectricity energy. The advantages of modified GSTARS3 model are:

1.) This model is user friendly.
2.) Running of this model is very rapidly.
3.) This model can be applied for large dams.
4.) This model does not need to special hardware.
5.) This model helps to user for determination of the optimum method of flushing.

Comparison between Figures 6 and 7 showed that reduction of volume of reservoir for case 2 (sediment yield is 1.2 times actual sediment yield) is more than its case 1 (sediment yield is equal to actual sediment yield). But final volume of reservoir for case 2 is equal to its case 1. This subject proved correctness of results of modified GSTARS3 model.

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