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The Evaluation of Three Methods of Uncertainty (MCS, LHS and Harr) in Dam Reservoir Sedimentation

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Abstract: Estimation of dam reservoir sedimentation volume is necessary for design and hydraulic structures management purposes. Different empirical and mathematical methods are employed in this regard. Due to different factors affecting sedimentation process and their randomness, uncertainties arise that causes failure and may force designers to consider necessary safety factors in their designs. Therefore, uncertainty analysis may introduces a better understanding of the effect of different input parameters and their contributions to the whole output error. In this study, the sediment discharge rate was estimated by employing different methods such as USBR and FAO justified coefficient. In these methods data collected from Nazloo River (in Tapik Station) were used. To calculate the trap efficiency Brune method and for specific weight Miller methods were used. The results of FAO justified coefficient method compared to other corresponding methods show better agreement with the measured ones. In this research, Mont Carlo Simulation (MCS), Latin Hypercube Sampling (LHS) and Harr's methods were investigated. The results show that the sediment discharge rate and the flow rate introduce the highest contribution to the whole uncertainty of sedimentation volume. Also, Harr's method show less uncertainty value compared to the Mont Carlo one.

Key words: Sedimentation volume, USBR, FAO, uncertainty analysis, mont carlo, LHS, Harr

INTRODUCTION

Uncertainties may arise due to natural variations in the phenomenon being considered, or to an incomplete understanding of mechanisms. Uncertainties may also arise from inaccurate characterization of important parameters or variables. Thus, engineering practice is frequently associated with decision making under uncertainty and physical or numerical models developed and used to simulate natural phenomena are often in reality probabilistic and hence, subject to analysis by rules of probability theory. Identifying the components of uncertainty relating to physical phenomenon and quantifying them can, therefore, improve decision making and the results (Huang, 1986; Mercer and Morgan, 1975).

Reservoir sedimentation varies with several factors such as sediment production, sediment transportation rate and sediment type, mode of sediment deposition, reservoir operation, reservoir geometry and streamflow variability. Sediment is transported as suspended sediment and bed load by streams and rivers entering a reservoir. The deposited sediments may consolidate by their weight and the weight of overlying water through time. The correct prediction of the amount of accumulated sediment behind the dam is one of the most important problems in hydraulic engineering. Empirical model, based on surveys and field observations, have been developed and applied to estimate annual Reservoir Sedimentation Load (RSL), Accumulated Reservoir Sedimentation Load (ARSL) and Accumulated Reservoir Sedimentation Volume (ARSV) after a given number of years of reservoir operation (Strand and Pemberton 1982; Morris and Fan 1998). Likewise, several mathematical models for predicting reservoir sedimentation have been developed based on the equations of motion and continuity for water and sediment (Chen, *et al*., 1978; Soares *et al*., 1982; Morris and Fan, 1998). However, empirical methods are still widely used in actual engineering practices (Butler, 1987; Ruddy, 1987; Shen and Julian, 1993). To estimate reservoir sediment inflow, reservoir sedimentation and reservoir sediment accumulation, a number of uncertainties arise: 1-quantity of streamflow; 2-quantity of sediment inflow into a reservoir; 3-sediment particle size; 4-specific weight of the deposits; and 5-reservoir size and operation (USBR, 1987) Fan (1988) obtained information on 34 streams, 18 watersheds and 12 reservoir-sedimentations models and stated that different models may give significantly

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different results even when using the same set of input data. Such an additional factor is known as model uncertainty and may be quite a large component of the overall uncertainty (Salas and Hyun, 1999).

Several methods of uncertainty analysis have been developed and applied in water resource engineering. The most widely used methods are First-order Variables Estimating (FOVE), Harr's Probabilistic Point Estimation method, Monte Carlo Simulation (MCS) (Ang and Tang, 1984). FOVE is based on linearizing the functional relationship that relates a dependent random variable and a set of independent random variables by Taylor series expansion (Yeh *et al*., 1986). This method has been applied in several water resources and environmental engineering problems involving uncertainty. Examples include: storm sewer design (Tang and Yen, 1972) ground-water flow estimation (Dettinger and Wilson, 1981) prediction of dissolved oxygen (Burges and Lettenmaier, 1975; Chadderton *et al*., 1982) subsurface flow and contaminant transport estimation (Sitar *et al*., 1978) and water surface profile of buried stream flowing under coarse material (Hansen and Bari, 2002). In Harr's method, average and variance of probabilistic variables and their correlations are used (Tung, 1993). If there are N variables, the number of cases (points) will be 2N which is considered an important advantage compared to the point estimate method proposed by Rosenblueth (1981). In cases where obtaining the derivatives are too complicated, Harr's method is considered a good substitute of the FOVE method. This method has been used in studying the spatial variation of river bed scouring (Yeh and Tung, 1993) and for uncertainty analysis incorporating marginal distribution (Chang *et al*., 1996). In Monte Carlo Simulation (MCS), stochastic inputs are generated from their probability distributions and are then entered into empirical or analytical models of underlying physical process involved in generating stochastic outputs. Then, the generated outputs are analyzed statistically to quantify the uncertainty of the output. Several examples of uncertainty analysis by MCS can be found in water resources and environmental engineering (Salas, 1993; Hipel and Mcleod, 1994; Melching, 1995). Some of them include ground-water flow estimation (Smith and Freeze, 1979; Jones, 1989) and water quality modeling (Warwick and Cale, 1986; Brutsaert, 1975) and in studying the spatiotemporal stochastic open-channel flow (Gates and Al-Zahrani, 1996). Scavia *et al*. (1981) made a comparison of MCS and FOVE for determining uncertainties associated with eutrophication model outputs such as plankton, zooplankton and nitrogen forms. They concluded that both FOVE and MCS agree extra in estimating the mean and variance of model estimates. However, MCS has the advantage of providing better information about the frequency distribution. Latin Hypercube Sampling (LHS) is used to generate random stochastic inputs in a stratified manner from the probability distributions. In this way the number of generated inputs can be reduced considerably as compared to MCS (McKay *et al*., 1979). Chang *et al*. (1993) used LHS to perform sensitivity and uncertainty analysis in his research. Yeh and Tung (1993) applied FOVE, the point estimate method proposed by (Rosenblueth, 1981) and LHS to analyze the uncertainty of migration of a pit. They pointed out the point estimate method yields a larger mean and variance than those obtained by FOVE and LHS methods. Furthermore, in studying the importance of stochastic inputs on the output by sensitivity analysis, LHS yields more information than the other two methods.

In this study, uncertainty analysis based on MCS, LHS and Harr's method is conducted to obtain the accumulated reservoir sedimentation volume. Then sensitivity analysis is performed to show the relative importance of stochastic inputs in estimating ARSV. In addition uncertainty analysis of ARSV through time is undertaken for single and combination of factors using MCS and LHS.

MATERIALS AND METHODS

Case study: Uncertainty analysis of reservoir sedimentation is applied to the Nazloo Reservoir that is located in the Urmia Lake Basin. Nazloo Dam was constructed in 2005. The reservoir capacity for Nazloo is 170×10^6 m^3. The basic information about streamflow and sediment data was obtained from West Azarbayjan Water Bureau in Iran (West Azarbayjan Water Bureau, 2002). The incoming suspended sediment load and the streamflow discharge are usually measured at hydrometric gauging stations and so, bed load calculated 10-30% of suspended load. The streamflow data at the Tapik gauging Station in Nazloo River are available for the 1950-2000 and the suspended sediment load for the 1964-2001. This is the nearest gauging station to Nazloo Reservoir. Table 1 shows the basic statistics of the streamflow data at the Tapik Station and the basic statistics of the suspended sediment load are listed in Table 2.

Annual sediment loads and accumulation rates: Reservoir sedimentation volume depends on the quantity of sediment inflow, the percentage of sediment inflow trapped by the reservoir and the specific weight of the deposited sediment taking into account the effect of

Table 1: The basic statistics of the streamflow data at the Tapik Station

Station	Length of record	Mean	Standard deviation	Coefficient of variation	Skewness coefficient
Tapik	1950-2000	13.032	6.108	0.469	1.019

Table 2: The basic statistics of the suspended sediment load at the Tapik Station

Station	Sample of suspended sediment load	Max. of suspended sediment load	Streamflow in max of suspended load	Date of sampling	Min. of suspended sediment load	Streamflow in min of suspended sediment load	Date of sampling
Tapik	498	323782.23	251.48	1994/4/1	1.16	0.38	1985/10/7

compaction with time. To evaluate suspended sediment and bed load in a number of hydrometric stations, the field data are divided to wet and dry time periods and total time periods. This separation is suitable for comparison between obtained results and real data because observation shows that dividing the field data to wet and dry time periods introduces better corresponding with real data. The wet and dry time periods division is based on the incoming daily streamflow discharge and their monthly average. In this regard, if the daily streamflow discharge is bigger than average, wet time periods occur and for dry time periods the daily streamflow discharge has to be smaller than average. Then other calculations have been performed for wet and dry time periods as well as total time periods.

Annual rating curves of suspended sediment and bed load may be represented as:

$$Qs = a_1 Q_w^{b_1} \quad (1)$$

$$Q_B = a_2 Q_w^{b_2} \quad (2)$$

Where Q_S = annual average suspended load (tons day^{-1}) in year t, Q_B = annual average bed load (tons day^{-1}) in year t; Q_W = annual average streamflow discharge (m^3 s^{-1}) in year t and a_1, b_1 and a_2, b_2 = rating curve coefficients for annual average suspended and bed load, respectively. Then total sediment inflow in year t (QT_t) is calculated as $QT_t = Q_{St} + Q_{Bt}$.

For estimating the annual sediment volume the USBR (1987) and the justified FAO (1981) coefficient were used. And then FAO method and its coefficients shows the best estimate compared to real data for annual average suspended and bed load. As in FAO method, coefficient (a) replaces (a$''$), where (a$''$) is defined as:

$$a'' = \frac{\bar{Q}s}{(\bar{Q}w)^b}$$

where $\bar{Q}_S$ = daily average suspended load (tones day^{-1}) for suspended load and daily average bed load (tones day^{-1}) for bed load, $\bar{Q}_W$ = daily average streamflow discharge (m^3 s^{-1}) and therefore, QS_t and QB_t are calculated with a new (a).

Using Brune's (1953) data, an empirical regression formula relating the trap efficiency versus the ratio of reservoir capacity and annual streamflows can be introduced as:

$$TE_t = a_3 + b_3 \{\log_{10}(C_{t-1} / IW_t)\}^2 \quad (3)$$

Where TE_t = trap efficiency (%) in year t, C_{t-1} = useful reservoir capacity (m^3) at the beginning of year t, IW_t = 31.536×10^6 QW_t stream flow (m^3) in year t and a_3,, b_3 = regression coefficients. The mean trap efficiency calculated with Brune Method is 96.58 that show no significant difference with real data. Then the total sediment load trapped in a reservoir in a given year, t, (RSL) is calculated as:

$$RSL_t = 3.65 QT_t \times TE_t \quad (4)$$

Where RSL is in tones; and the accumulated sediment in reservoir after t years is:

$$ARSL_t = ARSL_{t-1} + RSL_t t = 1, 2, \ldots \text{Where } ARSL_0 = 0 \quad (5)$$

After the sediment is trapped in the reservoir, it will be compacted through time by its own weight and the weight of the overlying water. Miller (1953) developed an empirical formula to estimate the average specific weight of sediments deposited after *t* years as:

$$W_t = W_1 + 0.4343K\left[(\frac{t}{t-1})Lnt - 1\right], t>1 \quad (6)$$

Where W_t = average sediment specific weight (kg m^{-3}) after t years; W_1 = specific weight of sediment in the first year; and K = consolidation constant. Both W_1 and K are functions of the type of reservoir operation and the size of sediment (Lane and Koelzer, 1943). Table 3 shows values of W_1 and K for various conditions of reservoir operation and sediment types such as clay, silt and sand. For a mixture of sediment, a weighted average of specific weights and consolidation constant must be used (7) and (8). (Lara and Pemberton, 1965):

$$W_1 = 0.01[W_1(c) P(c) + W_1(m)P(m) + W_1(s)P(s)] \quad (7)$$

Table 3: Initial specific weight W_1 (kg m^{-3}) and consolidation constant (Strand and Pemberton, 1982)

	Clay		Silt		Sand	
Type of reservoir operation	W_1 (c)	K (c)	W_1 (m)	K (m)	W_1 (s)	K (s)
Sediment always submerged or nearly submerged	416	256	1120	91	1500	0
Moderate to considerable reservoir drawdown	561	135	1140	29	1550	0
Reservoir normally empty	641	0	1150	0	1550	0
Riverbed sediments	941	0	1170	0	1550	0

$$K = 0.01[K(c)\,P(c) + K(m)P(m) + K(s)P(s)] \quad (8)$$

Where W_1(c), W_1(m) and W_1(s) = initial specific weight; K(c), K(m) and K(s) = consolidation constants; and P(c), P(m) and P(s) = percentages of clay, silt and sand, respectively.

To determine the specific weight of sediment, two methods have been used: 1- Miller and 2- Lane and Koelzer. The Miller's shows better results than the other one. Then, the average specific weight of sediment, W_t, is used to convert the mass of accumulated sediment in the reservoir into volume:

$$ARSV_t = 1000\ ARSL_t/W_t \quad (9)$$

By obtaining the $ARSV_t$, the useful capacity remaining in the reservoir at the end of year t, can be estimated by:

$$C_t = C_0\text{-}ARSV_t \quad (10)$$

Where C_0 = initial useful reservoir capacity (Salas and Hyun, 1999).

The uncertainty of annual stream flow is an important factor affecting the uncertainty of reservoir sedimentation. Stochastic time series models have been widely used in the literature for many water resources problems (Loucks *et al.*, 1981; Salas, 1993). Auto Regressive models (AR) have been the most commonly used models for annual streamflow simulation (Mcleod and Hipel, 1978; Salas *et al.*, 1980). AR(1) model defined as:

$$Qw_t = \mu + \phi_1(QW_{t-1}-\mu) + \varepsilon_t \quad (11)$$

Where μ = mean; ϕ_1 = lag-1 autoregressive coefficient and ε_t = normal random variable with mean zero and varianceσ^2_t. Then we have 10 sources of uncertainty for studying reservoir sedimentation; {a_1, b_1, a_2, b_2, a_3, b_3, P(c), P(m), P(s) and Q_w}.

The USBR method by applying the justified FAO coefficient shows the best fitting with real data. The accumulated sediment volume of Nazloo reservoir after a 10 years period of operation is equal to 7.85 Mm^3.

Uncertainty of reservoir sedimentation: The empirical model of estimating reservoir sedimentation there is various uncertain factors that affect reservoir sedimentation that may be categorized as follows: 1-those inputs associated with annual sediment rating curves for estimating annual sediment inflows such as regression coefficient a_1, b_1 and a_2, b_2 ; 2-those associated with the type of the incoming sediment such as the percentage of clay, silt and sand; 3-those associated with the regression equation for estimating the trap efficiency of the reservoir; and 4-those inputs associated with the variability of the water inflows to the reservoir.

RESULTS AND DISCUSSION

Uncertainty analysis of accumulated reservoir sediment volume with MCS and LHS: In applying the MCS method to generate the stochastic inputs, normally a large data set, for instance, n = 1000 is generated from the probability distribution of each stochastic input. For more details on MCS the reader is referred to Rief (1988).

The specific simulation procedure is summarized here: 1-Generate annual flows Qw_t(t = 1,…M) from (11) where M = simulation run years (30), n times that's needed for each method. 2-generate the other set of stochastic inputs (a_1, b_1, a_2, b_2, a_3, b_3, P(c), P(m), P(s)) n times. 3-using the obtained stochastic inputs, determine the stochastic output namely, the $ARSV_t$ and useful capacity at the end of year t, C_t, from (4), (5), (9) and (10), respectively. 4-obtain an array of n output for each t. 5-determine the statistical characteristics of the array $ARSV_t$ such as the mean, variance and coefficient of variation. The best probability distribution that's fitted with data set from Normal, Log Normal, Pearson, Log Pearson, Uniform and Exponential distribution were chosen and its result shown in Table 4.

An alternative to MCS sampling that reduces the number of sets generated inputs and consequently the number of generated outputs is the LHS method. The basic concept of LHS lies in generating random numbers of a stochastic input over its range in a stratified manner, such as the overall variability of the given stochastic input can reasonably be delineated by limited sample size. The properties of LHS are discussed by McKay (1988) and McKay *et al.* (1979). In the procedure of MCS or LHS, all stochastic inputs are assumed to be independent. For calculating ARSV, t=1,….,45, that is for each t, 1000

Table 4: Best probability distribution for 10 stochastic inputs

Inputs	Mean	Standard deviation	Distribution
a_1 (wet and dry periods)	10.651	5.302	Bivariate
b_1 (wet and dry periods)	2.156	0.247	Normal
a_1 (total periods)	18.559	4.817	Bivariate
b_1 (total periods)	1.957	0.106	Normal
a_2 (wet and dry periods)	4.904	2.365	Bivariate
b_2 (wet and dry periods)	2.111	0.237	Normal
a_2 (total periods)	5.174	0.508	Bivariate
b_2 (total periods)	1.372	0.039	Normal
a_3	100.068	1.646	Bivariate
b_3	-13.359	0.552	Normal
P(c)	20.720	-	Uniform
P(m)	46.840	-	Uniform
P(s)	32.440	-	Uniform
QW	13.032	6.108	Log normal

Table 5: Statistical characteristics of ARSV for 15, 30 and 45 years of reservoir operation considering the effect of individual factors (MCS method) for wet and dry time periods and total time periods

Time in years	Uncertain factors	Mean	Standard deviation	Coefficient of variation	Coefficient of skewness
15	C1	22548633	7253641.564	0.321	0.965
	C2 (total)	12654389	1236548.324	0.097	-1.234
	C2' (wet and dry)	15238974	1895426.324	0.124	-0.417
	C3	11456258	254789.145	0.022	-0.604
	C4	11569887	144626.320	0.012	-1.165
30	C1	35266412	10362565.555	0.294	0.520
	C2 (total)	29659874	3412661.415	0.115	-1.256
	C2' (wet and dry)	39658789	7454512.950	0.187	-0.608
	C3	30254785	526451.854	0.017	-0.623
	C4	28563247	298785.657	0.010	-1.045
45	C1	51666845	11452232.549	0.221	0.278
	C2 (total)	50987623	5525489.524	0.108	-0.524
	C2' (wet and dry)	65241321	10243698.421	0.157	-0.515
	C3	49587987	762541.110	0.015	-0.365
	C4	48545478	326471.547	0.007	-1.234

Considering the individual effect of the following uncertain factors: C1-Annual stream flow; C2-annual sediment inflow with uncertainty in suspended sediment and bed load rating curve parameters (a_1, b_1) and (a_2, b_2) respectively; C3-trap-efficiency curve with uncertainty in regression coefficient (a_3 b_3); and C4-percentage of sediment particles P(c), P(m) and P(s)

and 100 values were used for MCS and LHS, respectively (except annual streamflow that generated 451000 values).

In MCS and LHS well-known results from regression analysis also indicate that and are bivariate normally distributed (Mood *et al*., 1974). For predicting fraction of sediment type (Clay, silt and sand) assume that such fraction are uniformly distributed with lower and upper bounds that are obtained from the measurements and soil texture diagram. These fractions must be added up to 100%. a_3 and b_3 may be assumed to be bivariate normally distributed too.

For uncertainty analysis the uncertain factors affecting *ARSV* have been classified as follows:

C1 = Annual stream flow with constant model parameters as follows:

$$(\hat{\mu}\ \text{(mean)}, \phi_1\ \text{(lag}-1\ \text{autoregressive coefficient), and}\ \sigma_\varepsilon^2\ \text{(variance))}$$

C2 = Annual sediment inflow with uncertainty in suspended sediment and bed load rating curve parameters (a_1, b_1) and (a_2, b_2) respectively,

C3 = Trap-efficiency curve with uncertainty in regression coefficient (a_3, b_3),

C4 = Fraction of each type of sediment.

The results of uncertainty analysis of accumulated reservoir sedimentation volume, ARSV, in MCS and LHS methods are shown in Table 5 and 6, respectively for total time periods and wet and dry time periods considering the effect of each factor.

Then, the uncertainly of ARSV is determined considering the combined effect of various uncertain factors and the results in MCS and LHS methods are shown in Table 7 and 8, respectively for total and wet and dry time periods:

A = Annual stream flow;
B = Annual streamflow + annual sediment inflow
C = Annual stream flow + annual sediment inflow + trap efficiency curve;
D = Overall uncertainty.

Table 5 and 6 show that the largest coefficient of variation (that is considered as the indicator of uncertainty) corresponds to annual streamflow is 41% in LHS and 32% in MCS for t = 15 years and decreasing to

Table 6: Statistical characteristics of ARSV for 15, 30 and 45 years of reservoir operation considering the effect of individual factors (LHS method)

For wet and dry time periods and total time periods

Time in years	Uncertain factors	Mean	Standard deviation	Coefficient of variation	Coefficient of skewness
15	C1	15475681	6044961.222	0.415	1.228
	C2 (total)	9390222	821178.276	0.087	-1.611
	C2' (wet and dry)	11811972	1399181.820	0.118	-0.303
	C3	9498027	143182.713	0.015	-0.509
	C4	9133185	64088.013	0.007	-1.268
30	C1	30839415	8840089.982	0.287	0.486
	C2 (total)	26841409	2239439.911	0.083	-1.096
	C2' (wet and dry)	35202531	4945276.301	0.140	-0.559
	C3	27003062	424712.480	0.016	-0.497
	C4	25995848	168187.750	0.006	-1.270
45	C1	46843018	9048857.946	0.193	0.116
	C2 (total)	46166355	3789812.869	0.082	-0.858
	C2' (wet and dry)	61528912	9206223.951	0.15	-0.625
	C3	46334143	748594.111	0.016	-0.488
	C4	44641870	273053.882	0.006	-1.271

Considering the individual effect of the following uncertain factors: C1-Annual stream flow; C2-annual sediment inflow with uncertainty in suspended sediment and bed load rating curve parameters (a_1, b_1) and (a_2, b_2) respectively; C3-trap-efficiency curve with uncertainty in regression coefficient (a_3, b_3); and C4-percentage of sediment particles P(c), P(m) and P(s)

Table 7: Statistical characteristics of ARSV considering the combined effect of several factors (MCS method)

Time in years	Uncertain factors	Mean	Standard deviation	Coefficient of variation	Coefficient of skewness
a) for wet and dry time periods					
15	A	22548633	7253641.564	0.321	0.965
	B	24663581	6132854.328	0.249	0.257
	C	29844211	10088172.541	0.338	0.220
	D	29142557	9147788.783	0.314	0.962
30	A	35266412	10362565.555	0.294	0.520
	B	48657921	12698432.641	0.261	0.857
	C	52548893	16228754.330	0.309	-0.124
	D	50241635	20544673.254	0.409	0.657
45	A	51666845	11452232.549	0.221	0.278
	B	75422381	13665287.121	0.181	-0.198
	C	79248336	19662558.253	0.247	-1.241
	D	79568339	22654524.260	0.285	0.645
b) for total time period					
15	A	22548633	7253641.564	0.321	0.965
	B	19658881	6054298.841	0.308	0.805
	C	19022389	5555412.785	0.292	1.102
	D	18845217	4698520.525	0.249	1.250
30	A	35266412	10362565.555	0.294	0.520
	B	34528779	11882364.214	0.344	0.488
	C	34974682	11023358.527	0.315	0.362
	D	33120546	9862657.124	0.298	0.441
45	A	51666845	11452232.549	0.221	0.278
	B	50688962	11952481.130	0.236	-0.554
	C	50448025	11558215.200	0.229	-0.346
	D	50029684	12140631.682	0.243	-0.522

Considering the combined effect of various uncertain factors such as: A=(1)=annual stream flow; B=(1)+(2)=annual streamflow + annual sediment inflow; C=(1)+(2)+(3)=annual stream flow + annual sediment inflow + trap efficiency curve; D=(1)+(2)+(3)+(4)=overall uncertainty

19 and 22% respectively for t = 45 years. The factor with smallest effect on the ARVS is fraction of sediments that it's CV (coefficient of variation) is smaller than 1%. In annual sediment inflow CV and CS (coefficient of skewnees) doesn't show increasing or decreasing with the time, but CS is positive in annual streamflow and in other cases are negative. This suggests that the Probability Distribution Function (PDF) of ARSV for all t, may be well fitted by its distribution because positive and negative parameters are constant for each t. In summary, the coefficient of skewness for annual sediment inflow in total time periods is more than wet and dry time periods for each t and largest skewness is related to annual sediment inflow in total time periods for t = 15 in LHS and for t = 30 in MCS. In addition CV in annual sediment inflow with wet and dry time periods is larger than total time periods for each t.

Table 7 and 8 show that CV of $ARSV_t$ for case (D) is 29% for t = 15 in total time periods and 38% in wet and dry time periods in LHS method and decreases to 21% and 26% for t = 45, respectively and is 30% for t = 30 in total time periods and 41% in wet and dry time periods in MCS

Table 8: Statistical characteristics of ARSV considering the combined effect of several factors (LHS method)

Time in years	Uncertain factors	Mean	Standard deviation	Coefficient of variation	Coefficient of skewness
a) for wet and dry time periods					
15	A	15475681	6044961.222	0.415	1.228
	B	16005163	5645529.459	0.353	0.385
	C	19512069	8139592.555	0.417	0.375
	D	19447813	7390098.474	0.380	1.377
30	A	30839415	8840089.982	0.287	0.486
	B	38373229	9924081.652	0.259	1.292
	C	41787223	12514525.810	0.299	-0.065
	D	40964415	15226612.250	0.372	0.764
45	A	46843018	9048857.946	0.193	0.116
	B	61852714	10669407.690	0.172	-0.107
	C	63684024	14028865.730	0.220	-0.977
	D	63568339	16893741.200	0.266	0.578
b) for total time period					
15	A	15475681	6044961.222	0.415	1.228
	B	14300990	5822895.590	0.407	1.280
	C	14388699	5843704.043	0.406	1.231
	D	14364054	4119101.286	0.287	1.394
30	A	30839415	8840089.982	0.287	0.486
	B	30866453	9403080.890	0.305	0.283
	C	30964683	9162646.359	0.296	0.234
	D	29593949	7740731.524	0.262	0.307
45	A	46843018	9048857.946	0.193	0.116
	B	46729101	9354981.241	0.200	-0.361
	C	46935818	9130579.694	0.194	-0.386
	D	46585939	10018993.160	0.215	-0.685

Considering the combined effect of various uncertain factors such as: A = (1) = Annual stream flow; B = (1)+(2) = Annual streamflow + annual sediment inflow; C = (1)+(2)+(3) = Annual stream flow + annual sediment inflow + trap efficiency curve; D=(1)+(2)+(3)+(4)=overall uncertainty

Table 9: Correlation matrix (Harr's method)

	a_1	b_1	a_2	b_2	a_3	b_3	p(c)	p(m)	p(s)
a)For wet and dry time periods									
a1	1	-0/991	1	-0/991	-0/194	-0/207	-0/166	0/166	-0/166
b1	-0/991	1	-0/991	1	0/229	0/246	0/211	-0/211	0/211
a2	1	-0/991	1	-0/991	-0/192	-0/207	-0/165	0/165	-0/165
b2	-0/991	1	-0/991	1	0/231	0/247	0/212	-0/212	0/212
a3	-0/194	0/229	-0/192	0/231	1	0/986	0/976	-0/976	0/976
b3	-0/207	0/246	-0/207	0/247	0/986	1	0/941	-0/941	0/941
p(c)	-0/166	0/211	-0/165	0/212	0/976	0/941	1	-1	1
p(m)	0/166	-0/211	0/165	-0/212	-0/976	-0/941	-1	1	-1
p(s)	-0/166	0/211	-0/165	0/212	0/976	0/941	1	-1	1
b)for total time periods									
a1	b1	a2	b2	a3	b3	p(c)	p(m)	p(s)	
a1	1	-0/974	0/843	-0/816	0/115	0/196	0/017	-0/017	0/017
b1	-0/974	1	-0/811	0/835	-0/081	-0/181	0/033	-0/033	0/033
a2	0/843	-0/811	1	-0/974	-0/163	-0/113	-0/208	0/208	-0/208
b2	-0/816	0/835	-0/974	1	0/228	0/156	0/293	-0/293	0/293
a3	0/115	-0/081	-0/163	0/228	1	0/986	0/976	-0/976	0/976
b3	0/196	-0/181	-0/113	0/156	0/986	1	0/941	-0/941	0/941
p(c)	0/017	0/033	-0/208	0/293	0/976	0/941	1	-1	1
p(m)	-0/017	-0/033	0/208	-0/293	-0/976	-0/941	-1	1	-1
p(s)	0/017	0/033	-0/208	0/293	0/976	0/941	1	-1	1

Table 10: Statistical characteristics of ARSV for 15, 30 and 45 years of reservoir operation (Harr's method)

Time in years	Periods	Mean	Standard deviation	Coefficient of variation
For wet and dry time periods and total time periods				
15	Wet and dry	8295649.278	2226403.2	0.268
	Total	14312326.590	3957546.1	0.276
30	wet and dry	36874117.190	17944534	0.486
	total	30580374.500	10788631	0.352
45	wet and dry	54753224.980	15244885	0.278
	Total	52340020.590	7227623.9	0.138

method and decreases to 24% and 28% for t = 45, respectively. The CS of $ARSV_t$ doesn't follow any trend in data. These tables show some additional features of the results obtained; for example wet and dry time periods nearly show larger CV (uncertainty) than total time periods. This type of information is good for investigating reservoir sedimentation in different time periods and may be useful for estimating the risk of specified thresholds in accumulated reservoir sedimentation. In this method annual streamflow and annual sediment inflow are the most important factors that affect the uncertainty of ARSV especially annual streamflow. And two other factors are less important. In case (A) the probability that the reservoir would be 80% full after 45 years is practically zero but in case (D) it has larger probability than case (A). This result illustrates that a complete uncertainty analysis can provide a much more realistic evaluation and better optimization of reservoir design life.

Uncertainty analysis of accumulated reservoir sediment volume with Harr's method: Harr's method is a simple, effective and precise method. It uses the two first order moments of stochastic variables and not the probability distribution but it is easy in terms of calculation efforts. Harr's method is considered a good substitute for other methods. Different stages of this method can be summarized as:

- Identifying input physical parameters of each of the relationships and calculating its correlation matrix,
- Decomposition the correlation matrix to eigen vectors matrix and diagonal eigen values matrix (with MATLAB software)

$$CO = VLV^t \tag{12}$$

Where $V = (v_1, v_2, ...v_n)$ is eigen vectors matrix and $L = \lambda_1, \lambda_2 ..., \lambda_n$ is eigen value diagonal matrix,

- Calculating 2N intersection points where this couple of points is calculated from the following equation (Hosseini 2000; Soleimani, 2003):

$$X_{i\pm} = \mu \pm \sqrt{N} \begin{bmatrix} \sigma_1.......... \\ .\sigma_2........0 \\ .....-...... \\ 0.....-.... \\ ....\sigma_N \end{bmatrix} V_i \tag{13}$$

where μ = mean; σ_i = standard deviation of *i*th stochastic input; N = number of inputs; V_i = eigen vectors matrix

- Calculating $Y_{i\pm} = g\ (X_{ith})$ and $Y_{i\pm}^2 = g^2\ (X_{i\pm})$ for (i = 1, 2, …., N) where Y_i=model output and then calculate

$$\overline{Y_i} = \frac{Y_{i+} + Y_{i-}}{2} \text{ and } Y_i^2 = \frac{Y_i^2 + Y_{i-}^2}{2}$$

- Calculating the average and variance of different model output:

$$E(Y) = \frac{\sum_{i=1}^{N} \overline{Y_i}\lambda_i}{\sum_{i=1}^{N} \lambda_i} = \frac{\sum_{i=1}^{N} \overline{Y_i}\lambda_i}{N} \tag{14}$$

$$E(Y^2) = \frac{\sum_{i=1}^{N} \overline{Y}_i^2 \lambda_i}{N} \tag{15}$$

$$Var(Y) = E\ (Y^2) - E^2\ (Y) \tag{16}$$

- Compute model uncertainty with coefficient of variation. For an elaborate discussion on Harr's method the reader is referred to Hosseini (2000).

In Harr's Method, the set of stochastic inputs (a_1, b_1, a_2, b_2, a_3, b_3, P(c), P(m), P(s)) are generated 2N times, but annual flows Qw_t are separated from correlation matrix then generated 2N*t times with SIMLAB Software.

For Harr's method the correlation matrix are shown in Table 9. For calculating ARSV the algorithm described in previous section was used. Moreover, the parameter uncertainty of the annual flows has been considered. Table 10 shows the result of uncertainty analysis of ARSV for t = 1,….0, 45, from Harr's method. This method shows that the CV is 35% for t = 30 in total time periods and 48% in wet and dry time periods and decreases to 14 and 28% respectively for t = 45.

Sensitivity analysis: To determine the degree of influence of each stochastic input on the output uncertainty, sensitivity analysis was carried out (Salas, 1999). The concept here is that by sensitivity analysis the stochastic inputs that are more important to output uncertainty are selecte for detailed analysis. Sensitivity analysis can be made based on Harr and a more complete analysis based on MCS and LHS study can be undertaken. The result of the sensitivity analysis for each inputs based on Harr's are shown in Fig. 1.

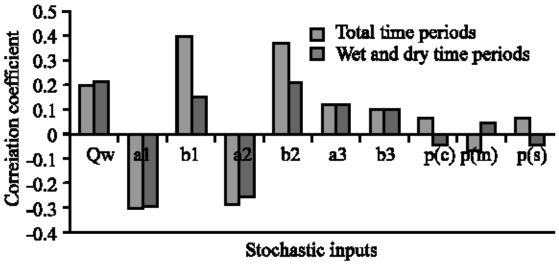

Fig 1: Comparison of sensitivities for all inputs (Harr's method)

$$SCC(x,y) = \frac{\sum_{i=1}^{n}(x_i - \mu_x)(y_i - \mu_y)}{\left[\sum_{i=1}^{n}(x_i - \mu_x)^2 \sum_{i=1}^{n}(y_i - \mu_y)\right]^{0.5}} \qquad (17)$$

Where μ_x = sample mean of stochastic input x; μ_y = sample mean of the output y; and n = sample size. Sensitivity analysis shows that annual streamflow followed by suspended sediment and bed load are the most important factors influencing ARSV, in both total and wet and dry time periods and percentage of sediments and trap efficiency follow the above inputs. In this study a_3 is the least significant factor.

CONCLUSION

Two types of conclusions can be drawn. First those related to the case study as:

- Annual streamflow and annual sediment inflow in Nazloo Dam are the most significant factors that influence accumulated reservoir sedimentation; trap efficiency and percentage of sediments are less important factors.
- In MCS, LHS and Harr's method, the uncertainty of accumulated reservoir sediment volume is 30, 29 and 35% in total time periods and 41, 38 and 48%for wet and dry time periods respectively.
- Sensitivity analysis shows that annual streamflow followed by suspended sediment and bed load are the most important factors influencing ARSV, in both total and wet and dry time periods and percentage of sediments and trap efficiency follow the above inputs. In this study a_3 is the least significant factor.

And the second are general conclusions as:

- In estimating reservoir sediment inflow, the FAO method (FAO, 1981) and its coefficients shows more reliable accumulated sediment volume compared to other methods.
- Wet and dry time periods estimate the uncertainty as more than in total time periods but to estimate sediment reservoir, wet and dry time periods have better correspondence with real data.
- In general, the results obtained by both MCS and LHS are similar. This research illustrates that the LHS method can provide adequate statistical information concerning the variability of accumulated reservoir sedimentation.
- Harr's method is a very simple method that in estimating uncertainty does not take into account the probability distribution of variables which might be considered as a disadvantage.
- Harr's method is used in water resources problems but due to that LHS method is an easy and precise method that calculates the effect of each uncertain factor, individually and in combination which is not the case in Harr's method. Therefore, the method of LHS is more recommended for design applications.
- The PDF of ARSV for all t, may be well fitted by its distribution because positive and negative parameters are constant for each t.

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