تحقیقات منابع آب ایران

Iran-Water Resources Research

سال سوم، شماره ۲، پاییز ۱۳۸۶

Volume 3, No. 2, Fall 2007 (IR-WRR)

1-11

آنالیز عدم قطعیت برآورد حجم رسوب مخازن (مطالعه موردی سد شهرچای)

مهسا واعظ تهرانی [۱] ، جمال محمد ولی سامانی [۲] و مجید منتصری [۳]

چکیده

پیش بینی مقدار رسوبات ورودی به مخازن سدها و نحوه توزیع و تجمع آن دارای اهمیت و پیچیدگی بالایی در طرح و بهره‌برداری مناسب چنین سازه‌های آبی است. روشهای ریاضی و تحلیلی متعدد و پیچیده‌ای برای شناخت فرآیند رسوب و برآورد رسوبات ورودی و نحوه رسوبگذاری آن در مخازن سدها ارائه گردیده است. تحلیل رسوب در مخازن سدها بر اساس چنین روش‌هایی همواره توام با خطای نسبی بوده که این برآورد خطای نسبی به عنوان Uncertainty (عدم قطعیت) در علوم مهندسی شناخته می‌شود. وجود عدم قطعیت در بر آورد پارامترهای طراحی سازه‌های آبی، یکی از دلایل اصلی عدم موفقیت مورد انتظار چنین سیستم‌هایی بوده و به کمیت درآوردن منابع عدم قطعیت می‌تواند یک گام اولیه و اصلی در تجزیه و تحلیل قابلیت اطمینان در عملکرد یک سازه آبی باشد. در طرح سیستم مخازن ذخیره (سدها)، تحلیل رسوب ورودی به مخزن جهت برآورد حجم مرده سد و نحوه ته نشینی رسوبات در سد از معیارهای اساسی طراحی به شمار رفته و منابع خطا یا عدم قطعیت در چنین تحلیلی می‌تواند ناشی از عدم امکان پیش بینی قطعی جریان ورودی، میزان رسوب، نوع رسوب و .... به مخزن باشد. در این تحقیق از روش‌هار (Harr) جهت تعیین میزان عدم قطعیت رسوبات متراکم شده مخزن در طول زمان (۱۵، ۳۰ و ۴۵ سال بعد از بهره برداری) در کل دوره آماری و دوره آماری خشک و تر استفاده شده است، به علاوه آنالیز حساسیت برای تعیین اهمیت فاکتورهای مختلف عدم قطعیت رسوبات مخزن انجام گرفته است. در این مطالعه سیستم مخزن ذخیره شهرچای در منطقه آذربایجان غربی مورد بررسی قرار گرفته و عدم قطعیت رسوبات تراکمی مخزن و تأثیر هر فاکتور عدم قطعیت روی رسوبات تجمعی مخزن در دو دوره آماری ذکر شده به دست آمده است. نتایج نشان می‌دهد دبی سالیانه جریان و بار رسوب از مهمترین فاکتورهای تعیین کننده عدم قطعیت حجم رسوبات سالانه مخزن و درصد رسوبات و راندمان تله اندازی دارای اهمیت کمتری می‌باشند. همچنین در این روش عدم قطعیت رسوبات تراکمی مخزن در کل دوره آماری ۰/۳۸۴ و در دوره آماری خشک و تر ۰/۲۴۴ به دست آمده است.

کلمات کلیدی: رسوب مخزن، روش هار، تحلیل عدم قطعیت

Uncertainty Analysis of Reservoir Sedimentation With Harr's Method Case Study: Shahar Chai Dam In Iran

M. Vaez Tehrani[1], J.M. Samani[2], and M. Montaseri[3]

Abstract

One of problems that affects the hydro-installation and reduces the useful life of dams, is sedimentation in the reservoir, which is unavoidable. In estimating reservoir sedimentation and accumulation, a number of uncertainties arise. These are related to the quantity of streamflow, sediment load, sediment particle size, and specific weight, trap efficiency, and reservoir operation. To evaluate suspended sediments and bed load in some hydrometric stations, separating the field data into wet and dry time periods and total time periods are used. Harr's method is used to quantify the uncertainty of accumulated reservoir sedimentation through time. To examine the importance of various factors on the uncertainty of accumulated reservoir sedimentation, sensitivity analysis was conducted. In this study, the effect of each uncertain factor, on the uncertainty of accumulated reservoir sedimentation through time has been examined for Shahar Chai Dam in northwestern Iran. The results show that in Harr's method, the uncertainty of accumulated reservoir sediment volume is 0.384 in total time periods and 0.244 for wet and dry time periods.

Keywords: Reservoir sedimentation, Harr's method, Uncertainty analysis.

۱- دانشجوی دوره دکترا سازه‌های آبی، گروه مهندسی آب، دانشگاه تربیت مدرس، تهران، ایران

۲- دانشیار گروه مهندسی آب، دانشگاه تربیت مدرس، تهران، ایران

۳- استاد یار گروه مهندسی آب، دانشگاه ارومیه، ارومیه، ایران

1 – pH.D student of Water Structures Eng., Tarbiat Modarres University, Tehran, Iran.

2 - Associate Professor of Water Structures Eng., Tarbiat Modarres University, Tehran, Iran

3 - Assistant Professor of Water Structures Eng., Urmia University, Urmia, Iran.

1-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 related 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, sediment type, mode of sediment deposition, reservoir operation, reservoir geometry, and streamflow variability. Sediment is transported as suspended sediments and bed loads 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. An empirical model, based on surveys and field observations, has 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 [see, for instance, Chen et al (1978), Soares et al (1982), and Morris and Fan (1998)]. However, empirical methods are still widely used in actual engineering practice (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) p.529]. Fan (1988) obtained information on 34 streams, 18 watersheds, and 12 reservoir-sedimentation models and stated that different models may give significantly 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 1999).

Several methods have been developed and applied for uncertainty analysis in water resource engineering, the most widely used of which 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. 1987), 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 (More details are introduced in 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 in which obtaining the derivatives are too complicated, Harr's method is considered a good substitute of the FOVE method. This method has been used for uncertainty analysis of sediment transport relationships (Yeh and Deng 1996), in studying the spatial variation of river bed scouring (Yeh and Tung 1993), and for uncertainty analysis incorporating marginal distribution (Chang and Yang 1997). In Monte Carlo Simulation (MCS), stochastic inputs are generated from their probability distributions and are then entered into empirical or analytical models of the 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. This way the number of generated inputs can be reduced considerably as compared to MCS (see 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 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.

2-Methodology

The incoming sediment load and the streamflow discharge are usually measured at hydrometric gauging stations, and a sediment rating curve is constructed. Incoming sediment is generally composed of suspended sediment and bed load. When the bed load cannot be obtained by measurements, it can be estimated by formulas [(Vanoni 1975) p.190]. The annual sediment rating curve is the relation between annual sediment load and annual streamflow discharge. Two methods can be considered for determining annual sediment rating curve from the daily sediment rating curve (Colby 1956). To evaluate suspended sediment and bed load for a number of hydrometric stations, the field data is divided into wet and dry time periods. The data separation improves the results compared to the one when the whole data is used. The division into wet and dry time periods is based on the incoming daily streamflow discharges and their monthly average. Wet time periods are those with a daily streamflow discharge that is bigger than the monthly average, while dry time periods are those with a daily streamflow discharge that is smaller than average. Then the other calculations have been performed for wet and dry time periods, as well as the total time periods. In estimating reservoir sediment inflow, the Food and Agricultural Organization method (Food and Agricultural Organization, 1981) and its coefficients give the best estimate compared to real data for annual average suspended and bed load.

For the estimation of $ARSV_t$, the following steps have been performed:

1- Calculating the daily rating curve of suspended sediment and bed load:

$$\log_{10} QSD = a_1^{'} + b_1^{'} \log_{10} QWD \quad (1)$$

$$\log_{10} QBD = a_2^{'} + b_2^{'} \log_{10} QWD \quad (2)$$

Where QSD = daily suspended load (tons/day); QBD = daily bed load (tons/day); QWD = daily average streamflow discharge (m^3/s); $a_1^{'}, b_1^{'}$ and $a_2^{'}, b_2^{'}$ = rating curve coefficients for suspended sediment and bed load respectively.

2- Calculating the corresponding annual rating curves of suspended sediment and bed load:

$$\log_{10} QS_t = a_1 + b_1 \log_{10} QW_t \quad (3)$$

$$\log_{10} QB_t = a_2 + b_2 \log_{10} QW_t \quad (4)$$

Where QS_t=annual average suspended load (tons/day) in year t, QB_t=annual average bed load (tons/day) in year t; QW_t=annual average streamflow discharge (m^3/s) in year t and a_1, b_1 and a_2, b_2 =rating curve coefficients for annual average suspended and bed load, respectively.

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

4- Calculating total sediment inflow in year t, $QT_t=QS_t+QB_t$

5- Calculating trap efficiency using Brune's (1953) data: [several empirical methods have been developed to estimate trap efficiency (Churchill 1948; Brune 1953; Brown 1958)]

$$TE_t=a_3+b_3 [\log_{10} (C_{t-1}/IW_t)]^2 \quad (5)$$

Where TE_t=trap efficiency (%) in year t, C_{t-1} =useful reservoir capacity (m^3) at the beginning of year t, $IW_t=31.536\times10^6\ QW_t$ streamflow (m^3) in year t and a_3, b_3= regression coefficients.

6- Calculating the total sediment load trapped in a reservoir in year t:

$$RSL_t=3.65\ QT_t\times TE_t \quad (6)$$

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

$$ARSL_t=ARSL_{t-1}+RSL_t \qquad t =1,\ 2,\ldots \quad (7)$$

Where $ARSL_0=0$

7- Estimating the average specific weight of sediments deposited after t years, using Miller (1953) formula:

$$W_t = W_1 + 0.4343K\left[\left(\frac{t}{t-1}\right)Lnt - 1\right], t>1 \qquad (8)$$

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 alternatively, both W_1 and K are functions of the type of reservoir operation and the size of sediment. (Lane and Koelzer 1943); Table 1 shows values of W_1 and K. For a mixture of sediment, a weighted average of specific weights and consolidation constant must be used as (Lara and Pemberton 1965):

$$W_1=0.01[W_1(c)\,P(c) + W_1(m)P(m)+W_1(s)P(s)] \qquad (9)$$
$$K=0.01[K(c)\,P(c) + K(m)P(m) + K(s)P(s)] \qquad (10)$$

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.

8- Calculating $ARSV_t$:
$$ARSV_t=1000\ ARSL_t/W_t \qquad (11)$$

9- Estimating C_t:
$$C_t=C_0-ARSV_t \qquad (12)$$

Where C_0=initial useful reservoir capacity.

3-Stochastic inputs

In the empirical models, the various uncertain factors that affect reservoir sedimentation may be categorized as follows:

-Inputs associated with annual sediment inflows such as regression coefficient a_1, b_1 and a_2, b_2 of step (3) and (4) respectively;

-Inputs associated with the type of the incoming sediment such as the percentage of clay, silt and sand;

-Inputs associated with the regression equation for estimating the trap efficiency of the reservoir; and

-Inputs associated with the variability of the water inflows to the reservoir.

Harr's method does not take into account the probability distribution of variables which might be considered as a disadvantage (Soleimani 2003). The uncertainty of annual streamflow is an important factor affecting the uncertainty of reservoir sedimentation. Stochastic time series models have been widely used in 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 [see, for instance, Mcleod and Hipel (1978) and Salas et al. (1980)]. AR(1) model is defined as:

$$QW_t= \mu + \phi_1(QW_{t-1}-\mu) + \varepsilon_t \qquad (13)$$

Where μ=mean; ϕ_1=lag-1 autoregressive coefficient; and ε_t= normal random variable with mean zero and variance σ_t^2 . 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}.

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 Harr's method can be summarized as:

-Identifying input physical parameters of each of the relationships and calculating its correlation matrix

-Decomposition of the correlation matrix (CO) to Eigen vectors matrix and Eigen diagonal values matrix

Table 1- Initial specific weight W_1 (kg/m^3) and consolidation constant [Strand and Pemberton (1982)]

Type of reservoir operation	Clay		Silt		Sand	
	$W_1(c)$	K(c)	$W_1(m)$	K(m)	$W_1(s)$	K(s)
Sediment always submerged(under continuous of water head) 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

$$CO = VLV^t \tag{14}$$

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:

$$X_{i\pm} = \mu \pm \sqrt{N} \begin{bmatrix} \sigma_1 .... \\ .\sigma_2 ....0 \\ .....-...... \\ 0.....-.... \\ ....\sigma_N \end{bmatrix} V_i \tag{15}$$

Where μ=mean; σ_i=standard deviation of ***i***th stochastic input; N=number of inputs; V=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 $\overline{Y}_i = \frac{Y_{i+} + Y_{i-}}{2}$ and $Y_i^2 = \frac{Y_i^2 + Y_{i-}^2}{2}$

-Calculating the average and variance of different model outputs:

$$E(Y) = \frac{\sum_{i=1}^{N} \overline{Y}_i \lambda_i}{\sum_{i=1}^{N} \lambda_i} = \frac{\sum_{i=1}^{N} \overline{Y}_i \lambda_i}{N} \tag{16}$$

$$E(Y^2) = \frac{\sum_{i=1}^{N} \overline{Y}_i^2 \lambda_i}{N} \tag{17}$$

$$Var(Y) = E(Y^2) - E^2(Y) \tag{18}$$

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

Sometimes when a large number of stochastic input is involved in determining the output, sensitivity analysis may be carried out to determine the degree of influence of each stochastic input on the output uncertainty, C_i.

In Harr's method a linear regression relationship between x's, input parameters, and output, Y can be considered, as the following:

$$Y = a_0 + \sum_{i=1}^{N} a_i x_i + e \tag{19}$$

Where a_0 is the interception value of the line with y axis, a_i refers to regression coefficients that show the sensitivity coefficients, and e is indicating the model error. Due to the dimensional problems, it is recommended to centralize the output parameter and then by standardizing (Y-Y) and input parameters, the regression can be conducted. In this case, coefficients will indicate the output variation for a variation of input parameters equal to one standard deviation. Then C_i values which indicate the uncertainty of the input parameter can be calculated from the following relationship:

$$C_i = \frac{SSR_i}{SSR} R^2 \quad \text{For } i=1,2,\ldots,N \tag{20}$$

In which SSR_i is the summation of square values of the ***i***th input stochastic parameter from the regressed line and SSR is the summation of SSR_i for the independent input parameters. For more details the reader is referred to McKay (1988).

The concept here is that by sensitivity analysis stochastic input more important to output uncertainty is selected for detailed analysis.

4-Procedural steps

The uncertainty in predicting accumulate sediment in a reservoir is an important aspect in the design and management of the reservoir. In this section, the uncertainty of accumulated sediment in the reservoir throughout a number of years of operation is considered by Harr's methods. The procedure steps are summarized here:

1- Generate annual flows Qw_t(t=1,…M) from (13) model where M=simulation run years, n times. 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)) 2n intersection points based on Harr's method described in the previous section. 3- Using the obtained stochastic input, determine the stochastic output namely, the $ARSV_t$ and useful capacity at the end of year t, C_t, from (6), (7), (11) and (12) 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, coefficient of variation, and coefficient of skewness.

5-Application

Uncertainty analysis of reservoir sedimentation is applied to the Shahar Chai reservoir, located in the Urmia Lake Basin. Shahar Chai Dam was constructed in 2005. The reservoir capacity for Shahar Chai is 221 $\times 10^6$ 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, based on expert's local estimation bed load calculated 10-30% of suspended load. The streamflow data at the Band gauging Station in Shahar Chai River are available for the years 1949-2001 and the suspended sediment load for the years 1964-2001. This is the nearest gauging station to Shahar Chai Reservoir. Table 2 shows the basic statistics of the streamflow data at the Band Station and the basic statistics of the suspended sediment load are listed in Table 3.

The corresponding annual rating curve equations are listed in Table 4. Mean values and standard deviations of annual rating curve parameters (a_1, b_1) and (a_2, b_2) in dry and wet time periods and total time periods are listed in Table 5. In addition, the annual rating curve for both suspended sediment and bed load in wet and dry time periods and total time periods are constructed in logarithmic coordinates as shown in Figs 1 and 2. The correlation coefficient between regression coefficients are -0.9393 and -0.974 for suspended sediment and bed load in total time periods and -0.9177, -0.9597 in wet and dry time periods. The lower and upper bounds for each fraction which are denoted as P(c), P(m) and P(s) listed in Table 5 were taken from field measurements and soil texture diagrams. The estimated mean and standard deviation of each regression coefficient, (a_3, b_3) are listed in Table 5 as well. The correlation coefficient between a_3 and b_3 is -0.694. In summary, the 9 stochastic inputs have been characterized.

For Harr's method the correlation matrix are shown in Table 6. For calculating ARSV the algorithm described in previous sections was used. Moreover, the parameter uncertainty of the annual flows has been considered.

6-Results

For calculating ARSV, t=1,…., 60, that is for each t, 9 values of $ARSV_t$ for Harr's are obtained that are used for statistical analysis, (except annual streamflow that generated 60×9 values).

Table 7 shows the result of uncertainty analysis of ARSV for t=1,…., 60, from Harr's method. In addition, the result of the sensitivity analysis for each input based on Harr's are shown in Fig 3.

Table 2- Basic statistics for streamflow data at the Band Station

Station	Length of record	Mean flow (m^3/s)	Standard deviation	Frequency of measurement	Sample of streamflow data points
Band	52	5.325	2.095	Every day	18250

Table 3- Basic statistics for the suspended sediment load at the Band Station

Station	Length of record	Mean (tons/day)	and Minimum Maximum	Frequency of measuring
Band	37	2906.21	0.19 and 30013.7	Two or three per month

Table 4- Annual rating curve for wet and dry time periods and total time periods and trap efficiency curve

Types	Regression equations
Annual suspended sediment(wet and dry periods)	$QS_t=23.381QW_t^{2.2019}$
Annual bed load(wet and dry periods)	$QB_t=11.785QW_t^{1.7082}$
Annual suspended sediment(total periods)	$QS_t=41.863QW_t^{2.0275}$
Annual bed load(total periods)	$QB_t=15.978QW_t^{1.6277}$
Trap efficiency	$TE_t=99.508-13.547\{\log_{10}(C_{t-1}/IW_t)\}^2$

QW_t= annual average streamflow discharge (m^3/s) in year t; QS_t= annual average suspended load (tons/day) in year t; QB_t=annual average bed load (tons/day) in year t; TE_t=trap efficiency (%) in year t, C_{t-1} =useful reservoir capacity (m^3) at the beginning of year t, $IW_t=31.536\times10^6\ QW_t$ stream flow (m^3) in year t

Table 5- Statistical properties (mean, standard deviation and type of distribution) of inputs

Inputs	Lower bound	Upper bound	Mean	Standard deviation	Distribution
a_1(wet and dry periods)	—	—	29.831	12.460	Bivariate
b_1(wet and dry periods)	—	—	2.104	0.316	Normal
a_1(total periods)	—	—	42.015	20.613	Bivariate
b_1(total periods)	—	—	2.106	0.352	Normal
a_2(wet and dry periods)	—	—	12.942	3.406	Bivariate
b_2(wet and dry periods)	—	—	1.669	0.179	Normal
a_2(total periods)	—	—	15.530	4.147	Bivariate
b_2(total periods)	—	—	1.668	0.178	Normal
a_3	—	—	99.508	1.5414	Bivariate
b_3	—	—	-13.547	0.5168	Normal
P(c)	12	28	26	—	Uniform
P(m)	50	72	54	—	Uniform
P(s)	20	50	20	—	Uniform
QW	—	—	5.325	2.095	Log normal

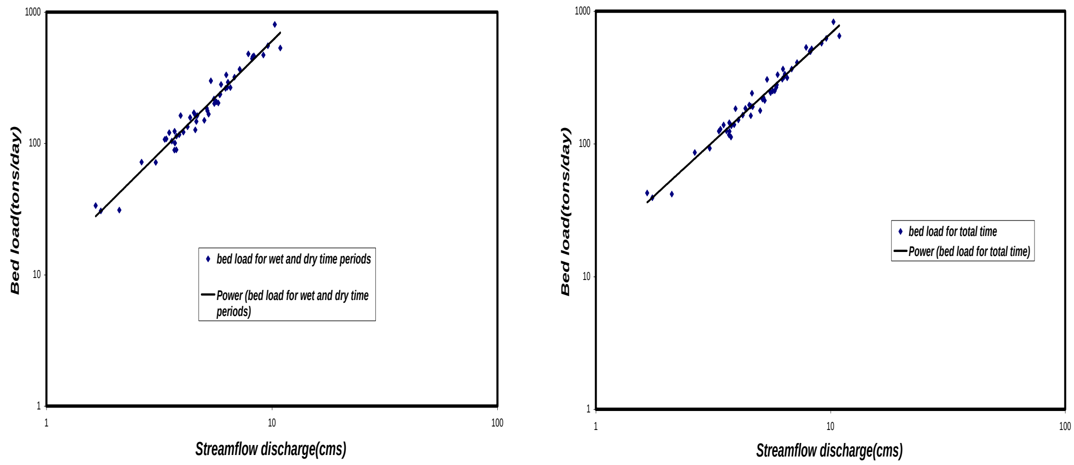

Fig 1- Annual sediment rating curve for bed load in a: wet and dry time periods and b: total time periods

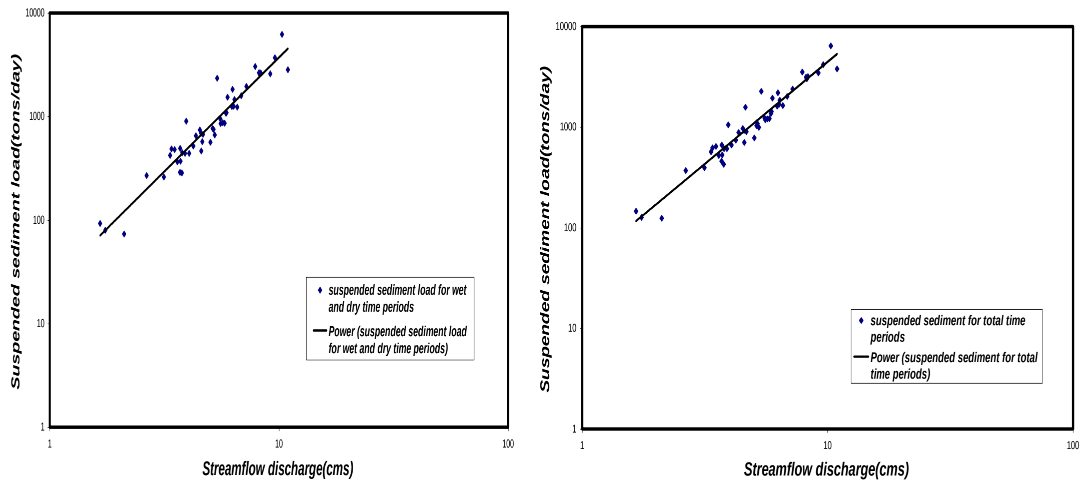

Fig 2- Annual sediment rating curve for suspended sediment in a: wet and dry time periods and b: total time periods

Table 6- Correlation matrix between input parameters (Harr's method)
a)for wet and dry time periods b) for total time periods

	a1	b1	a2	b2	A3	b3	p(c)	p(m)	p(s)
a1	1.000	-0.968	0.963	-0.974	0.456	0.385	-0.405	0.405	-0.405
b1	-0.968	1.000	-0.922	0.970	-0.481	-0.385	0.471	-0.471	0.471
a2	0.963	-0.922	1.000	-0.983	0.358	0.314	-0.363	0.363	-0.363
b2	-0.974	0.970	-0.983	1.000	-0.358	-0.287	0.401	-0.401	0.401
a3	0.456	-0.481	0.358	-0.358	1.000	0.984	-0.513	0.513	-0.513
b3	0.385	-0.385	0.314	-0.287	0.984	1.000	-0.453	0.453	-0.453
p(c)	-0.405	0.471	-0.363	0.401	-0.513	-0.453	1.000	-1.000	1.000
p(m)	0.405	-0.471	0.363	-0.401	0.513	0.453	-1.000	1.000	-1.000
p(s)	-0.405	0.471	-0.363	0.401	-0.513	-0.453	1.000	-1.000	1.000

	a1	b1	a2	b2	a3	b3	p(c)	p(m)	p(s)
a1	1.000	-0.966	0.988	-0.965	0.026	-0.067	-0.643	0.643	-0.643
b1	-0.966	1.000	-0.972	0.994	0.101	0.177	0.596	-0.596	0.596
a2	0.988	-0.972	1.000	-0.983	0.026	-0.055	-0.570	0.570	-0.570
b2	-0.965	0.994	-0.983	1.000	0.060	0.129	0.551	-0.551	0.551
a3	0.026	0.101	0.026	0.060	1.000	0.984	0.338	-0.338	0.338
b3	-0.067	0.177	-0.055	0.129	0.984	1.000	0.451	-0.451	0.451
p(c)	-0.643	0.596	-0.570	0.551	0.338	0.451	1.000	-1.000	1.000
p(m)	0.643	-0.596	0.570	-0.551	-0.338	-0.451	-1.000	1.000	-1.000
p(s)	-0.643	0.596	-0.570	0.551	0.338	0.451	1.000	-1.000	1.000

a_1,b_1= rating curve coefficients for annual average suspended load; a_2,b_2= rating curve coefficients for annual average bed load; a_3,b_3= regression coefficients for trap-efficiency curve and P(c), P(m) and P(s) = percentage of clay, silt, and sand, respectively.

Table 7- Statistical characteristics of ARSV for 15, 30 and 45 years of reservoir operation (Harr's method) for wet and dry time periods and total time periods

Time in years	Periods	Mean	Standard deviation	Coefficient of variation
15	wet and dry	6977646.006	1576590.42	0.226
	total	6263902.22	2406155.08	0.384
30	wet and dry	11605907.16	2420181.26	0.209
	total	13919347.65	3700629.88	0.266
45	wet and dry	22584853.63	5513099.27	0.244
	total	24151160.66	6065491.06	0.251

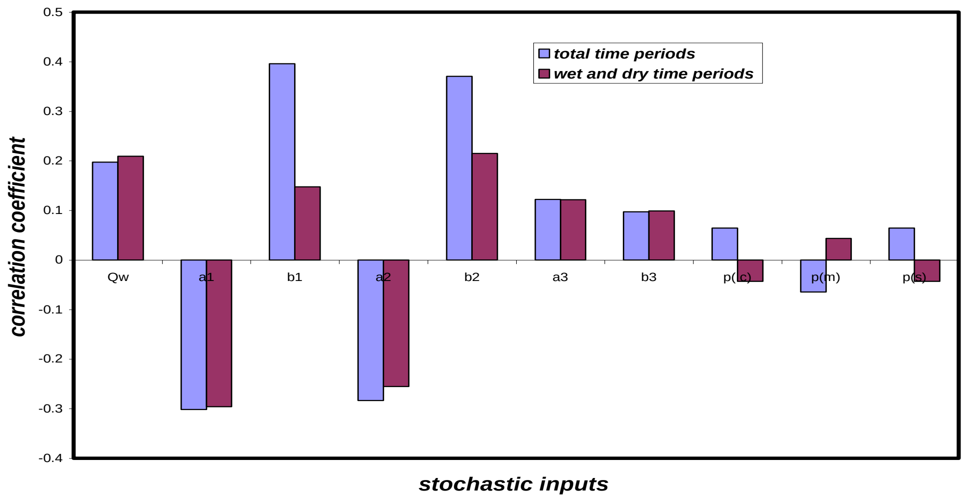

Fig 3- Comparison of sensitivities for all inputs (Harr's method)

Also, total time periods show larger coefficients of variation (uncertainty) than do wet and dry time periods. In this method annual streamflow and annual sediment inflow are the most important factors that affect the uncertainty of ARVS, especially the annual streamflow. The two other factors are less important. This result illustrates that a complete uncertainty analysis can provide a much more realistic evaluation and better optimization of reservoir design life. So, Harr's method shows that the CV is 38% for t = 15 in total time periods and 23% in wet and dry time periods and decreases to 25% for t = 45 for all periods. In addition, sensitivity analysis shows that suspended sediment and bed load followed by annual steamflow are the most important factors influencing ARSV, in both total and wet and dry time periods. Trap efficiency and the percentage of different sediment type rank as the less important factors. In this study the percentage of silt is a less significant factor.

In this study, the result of uncertainty analysis with Harr's method shows good agreement with Monte Carlo simulation and LHS results employed by Salas (1999).

7-Conclusions

1- Annual streamflow and annual sediment inflow are the most significant factors that influence accumulated reservoir sedimentation, trap efficiency and percentage of sediments are less important factors.

2- In Harr's method, the uncertainty of accumulated reservoir sediment volume is 37% in total time periods and 31% for wet and dry time periods.

3- Sensitivity analysis shows that suspended sediment and bed load followed by annual streamflow are the most important factors influencing ARSV, in both total and wet and dry time periods, and trap efficiency and percentage of different are less important. In this study percentage of silt is the least significant factor.

4- Wet and dry time periods estimate the uncertainty less than total time periods but to estimate sediment reservoir, wet and dry time periods have better correspond with real data.

5- Harr's method is a very simple method that estimates uncertainty and does not take into account the probability distribution of variables which might be considered as a disadvantage. This method is recommended in water resources problems.

8-References

Ang, A. H. S. and Tang, W. H. (1984). *Probability concepts in engineering planning and design*. Vol.2, *Decision, Risk and Reliability*, John Wiley, New York.

Brown, C. B. (1958). Sediment transportation. *Engineering Hydraulics*, H. E. Rouse, ed, Wiley, New York.

Brune, G. M. (1953). Trap efficiency of reservoirs. *Trans. AGU*, 34(3), pp. 407-418.

Brutsaert, W. F. (1975). Water quality modeling by Monte Carlo Simulation. *Water Resources Bulletin*, 11, pp. 175-186.

Burges, S. J., and Lettenmaier, D. P. (1975). Probabilistic methods in stream quality management. *Water Resour. Bull.*, 11(1), pp. 115-130.

Butler, D. L. (1987). Sedimentation discharge in Rock Creek and the effect of sedimentation rate on the proposed Rock Creek Reservoir Northern Colorado. *Water Resour. Investigation Rep.* 87-4026, U.S. Geological Survey, Denver.

Chadderton. R. A. Miller, A. C., and McDonnell, A. J. (1982). Uncertainty analysis of dissolved oxygen model. *J. Envir. Engrg. Div.*, ASCE, 108(5), pp. 1003-1013.

Chang, C. H., Yang, J. C., and Tung, Y. K. (1993). Sensitivity and uncertainty analysis of a sediment transport model: A global approach. *Stochastic Hydrol. Hydr*., 7, pp. 299-314.

Chang, C. H., Yang, J. C., and Tung, Y. K. (1997). Uncertainty analysis by point estimate methods incorporating marginal distribution. *J. of Hydraulic Engineering*, ASCE, 123(3), pp. 244-250.

Chen, Y. H., Lopez, J. L., and Richardson, E. V. (1978). Mathematical modeling of sediment deposition in reservoir. *J. Hydr. Div.*, ASCE, 104(12), pp. 1605-1616.

Churchill, M. A. (1948). Discussion of analysis and use of reservoir sedimentation data. by L. C. Gottschalk. Proc., *Fed. International Sedimentation Conf.*, pp. 139-140.

Colby, B. R. (1956). Relationship of sediment discharge to streamflow. Open File Rep., U.S. Geological Survey, *Water Resources Division*, Washington, D. C.

Dettinger, M. D., and Wilson, J. L. (1981). First order analysis of uncertainty in numerical models of groundwater flow, Part 1. Mathematical development. *Water Resour. Res.*, 17(1). pp. 149-161.

Fan, S. S. (1988). Twelve selected computer stream sedimentation models developed in United States. Interagency Advisory Committee on Water Data. Subcommittee on sedimentation, *Federal Energy Regulatory Commission,* Washington, D.C.

FAO. (1981). Arid Zone Hydrology for Agricultural Development.

Gates, K., and Al-Zahrani, M. A. (2002). Spatiotemporal stochastic open-channel flow. *J. of Hydraulic Engineering*, ASCE, 122(11), pp. 641-661.

Hansen, D., and Bari, R. (1996). Uncertainty in water profile of buried stream flowing under coarse material. *J. of Hydraulic Engineering*, ASCE, 128(8), pp. 761-773.

Hipel, K. W. and McLoed, A. L. (1994).Time series modeling of water resources and environmental systems. *Development in water science*, 45, Elsevier Science, New York.

Hosseni, S. M. (2000). Statistical evaluation of the empirical equation that estimate hydraulic parameters floe through rockfill. *Stochastic Hydraulics 2000*, eds.Wang, Z. Y. and Hu, S. X. Balkema, Rotterdam.

Huang, K. Z. (1986). Reliability Analysis of Hydraulic Design of Open Channel. Stochastic and Risk Analysis in Hydraulic Engineering, *Water Resources Publications*, ed. Yen, B.C., Littleton, Co.

Jones, l. (1989). Some results comparing Monte Carlo simulation and first order Taylor series approximation for steady groundwater flow. *Stochastic Hydrol. Hydr.*, 3, pp. 179-190.

Lane, E. W. and Koelzer, V. A. (1943). Density of sediment deposited in reservoirs. *A study of methods used in measurement and analysis of sediment load in streams, Rep.* No. 9, Hydraulic Lab, Univ. of Iowa.

Lara, J. M., and Pemberton, E. L. (1965). Initial unit weight of deposited sediments. *Proc. Fed. Interagency Sedimentation Conf.*, U.S. agriculture Research Service Publ. No. 970, pp. 818-845.

Loucks, D. P., Stedinger, J. R. and Haith, D. A. (1981). *Water resources systems planning and analysis.* Prentice hall, Englewood Cliffs, N.J.

McKay, M. D. (1988). Sensitivity and uncertainty analysis using a statistical sample of input values. Proc. Fed. *Uncertainty analysis*, Y. Ronen, ed., CRC, Boca Raton. Fla., pp. 145-185.

McKay, M. D., Beckman, R. J. and Conover, W. J. (1979). A comparison of three methods for selecting values of input variables in the analysis of output from a computer node. *Technometrics*. 21(2), pp. 239-245.

McLeod, A. L. and Hipel, K. W. (1978). Simulation procedures for Box Jenkins models. *Water Resour. Res*., 14(5), pp. 969-980.

Melching, C. S. (1995). Reliability estimation. *Computer models of watershed hydrology*, V. P. Singh, ed., Water Resources Publication, Littleton, Colo., pp. 69-118.

Mercer, L. J. and Morgan, W. D. (1975). Evaluation of a probability approach to uncertainty in benefit-cost analysis. Technical Report, Contribution No: 149, *California Water Resources Centre*, University of California, Davis.

Miller, C. R. (1953). *Determination of the unit weight of sediment for use in sediment volume computations.* Bureau of reclamation, Denver.

Morris, G. L. and Fan, J. (1998). *Reservoir sedimentation handbook.* McGraw-Hill , New York.

Rosenblueth, E. (1981). Two-point estimates in probabilities. *Appl. Math. Modeling,* 5 , pp. 329-335.

Ruddy, B. C. (1987). Sediment discharge in Muddy Creek and the effect of sedimentation rate on the proposed Wolford Mountain Reservoir near Kremmling, Colorado. *Water Resour. Investigation Rep.* 87-4011. U.S. Geological Survey, Denver.

Salas, J. D. (1993). Analysis and modeling of hydrologic time series. *Handbook of hydrology*, D. R. Maidment, ed., Chapter 19. McGraw-Hill, New York.

Salas, J. D., and Hyun-Suk Shin (1999), Uncertainty Analysis of Reservoir Sedimentation. *Journal of Hydraulic Engineering.* 125(4). pp. 339-350.

Salas, J. D., Delleur, J. W., Yevjevich, V., and Lane, L. J. (1980), *Applied modeling of hydrologic time series.* Water Resources Publications. Littleton, Colo.

Scavia, D., Powers, W. F., Canale, R. P., and Moody, J. L. (1981), Comparison of first-order error analysis and Monte Carlo simulation in time dependent lake eutrophication models . *Water Resour. Res*, 17(4), pp. 1051-1059.

Shen, H. W. and Julien, P. Y. (1993). Erosion and sediment transport. *Handbook of hydrology*, D. R. Maidment, ed., Chapter 12. McGraw-Hill, New York.

Sitar, N. Cawlfield, J. D. and der Kiureghian, A. (1978). First-order reliability approach to stochastic analysis of subsurface flow and contaminant transport. *Water Resour. Res*, 23(5), pp. 794-804.

Smith, L. and Freeze, R. A. (1979). Stochastic analysis of steady state groundwater flow in as bounded domain. 2. Two-dimensional simulations. *Water Resour. Res,* 15(6), pp. 1543-1559.

Soares, E. F., Unny, T. E. and Lennox, W. C. (1982). Conjunctive of deterministic and stochastic models for predicting sediment storage in large reservoirs. *J. Hydrol.* 59, pp. 83-105.

Soleimani, A. (2003). Uncertainty analysis of routed outflow in rockfill dam, Water department, *Tarbiat Modares University,* Tehran, Iran.

Strand, R. L., and Pemberton, E. L. (1982). *Reservoir sedimentation. Technical Guideline for Bureau of Reclamation* U.S. Dept. of Interior, Bureau of reclamation, Denver.

Tang, W. H., and Yen, B. C. (1972). Hydrologic and hydraulic design under uncertainties. *Proc, but. Symp. on Uncertainties in Hydrology and Water Resour. Sys.,* Vol. 2. University of Arizona. Tucson, pp. 868-882.

Tung, Y. K. (1993). Uncertainty and reliability analysis. In: *Water Resources Handbook,* Chapter 7, ed. Mays, L. W., McGraw-Hill, New York.

U.S. Bureau of reclamation. (1987). *Design of small dams*. Water Resources Technical Publication. U.S. Government Printing Office, Washington, D.C.

Vanoni, V. A. (1975). *Sedimentation engineering.* Prepared by the ASCE Task Committee for the preparation of the Manual on Sedimentation Committee of the Hydraulics Division, ASCE, Reston, Va.

Warwick, J. J., and Cale, W. G. (1986). Effects of parameters uncertainty in stream modeling. *J. Envir. Engrg.,* ASCE, 112(3), pp. 479-489.

West Azarbayjan Water Bureau (2002): Introduction of Rivers in West Azarbayjan State. Water Resources Technical Publications, Urmia, Iran, pp. 23-46.

Yeh, B. C., Cheng, S. T., and Melching, C. S., (1986). First-order reliability analysis. *Stochastic and risk analysis in hydraulic engineering,* B. C. Yen, ed., Water Resources Publication, Littleton, Colo., pp. 1-36.

Yeh, K. C. and Deng, S. L. (1996). Uncertainty Analysis of Sediment Formulas, in Stochastic Hydraulics, 96, eds. Tickle et al.

Yeh, K. C. and Tung, Y. K., (1993). Uncertainty and Sensitivity Analysis of Pit-Migration Model, *Journal Of Hydraulic Engineering,* ASCE, Vol.119, No.2.

Submitted: November 11, 2004
Revised: June 6, 2007
Accepted: July 8, 2007