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Estimation of Sediment Volume in Karaj Dam Reservoir (Iran) by Hydrometry Method and a Comparison with Hydrography Method

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Abstract

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Estimation of sediment volume in the reservoirs is an important management criterion in water use. Many methods are used for this purpose, including hydrography, remote sensing, hydrometry and mathematical and computer models. The high cost of field methods such as hydrography required other methods to be investigated more seriously. In the present research, the hydrometry method was used to estimate the sediment volume in Karaj Dam Reservoir, located on the southern slope of Mount Alborz of Iran. The estimation is based on evaluation of both suspended and bed-load sediments. Although the sediment rating curve method is not common in general, using corrected models based on effective factors of sediment transfer, such as time of measurement, have increased the model efficiency. For this purpose, the daily and annual suspended loads were estimated in two hydrometric stations of Seera and Beylaghan (inlet and outlet hydrometric stations of Karaj Dam) using daily water flow rates and monthly sediment rating equations. Because the empirical methods of bed load sediment did not give acceptable results, the Karaushev curve (which has suitable compatibility with Iranian rivers) was used and the ratio of bed load to suspended load was obtained based on the river slope at hydrometric stations. By using total sediment load and average sediment density, the volumes of sediment were calculated for dam inlet and outlet hydrometric stations. Subtraction of the two volumes gave the stored annual sediment in reservoir of about 406,000 m^3. The sediment volume resulting from the hydrography method (from dam primary and secondary area-volume curves) was 416,000 m^3, which gave 97% collation, and the trapping efficiency of the Karaj Dam was calculated to be 80%.

Key Words: sedimentation, hydrometry, hydrography, sediment rating curve, Karaushev curve, trap efficiency, Karaj Dam, Iran

Introduction

When a dam impounds a river, the inlet flow velocity to the reservoir decreases, and part of transported sediment is deposited in the reservoir (Chen *et al.* 1978). The dam and reservoir act like a sediment trap, and after depositing sediment, relatively clean water is released through the gates and weirs (Kolhari 1999). These natural reservoirs have irregular shapes and non-uniform hydraulic conditions, often undefined, so the sedimentation phenomenon is complicated and random in nature (Mousavi and Samadi Brojeni 1996).

The amount of sediment yield depends on different factors, such as watershed area, vegetation, geology and formations of the region, as well as temporal and spatial distribution and

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Table 1.-The technical characteristics of Karaj dam (Farhangi 1993).

Name of Dam	Name of river	Dam location	Type of dam	Type of weir	Length of crest	Height from Foun.	Total Capacity	Useful Capacity
Karaj	Karaj	North of Karaj	Concrete arch	Gate	390m	180m	205 MCM	195 MCM

duration and intensity of rainfall (Khalaj Amir Hosseini and Karimzadeh 1999). Each year about 20 billion tons of sediments are transported by the rivers of the world and deposited in still water (Mirbagheri 1989). In Iran over 100 million m^3 of storage dam capacity is lost due to sedimentation (Jalalian 1994). In addition, the World Bank estimated the annual cost of lost reservoir capacity due to sedimentation at $6 billion (Fan 1999); therefore, estimation of sediment volume deposited in the reservoir is important for multiple reasons.

Sediment volume estimation in reservoirs of dams is very complicated due to existence of unknown factors for evaluation of reservoir sediment and its volume. These factors depend upon flow rate, total sediment load, size of the sediment, density, trap efficiency and reservoir yield (Salas and Sukshin 1999).

Several methods are used to determine the amount of sediment in reservoirs, such as hydrography, mathematical and computer models, hydrometry, and remote sensing, but due to differences in the techniques, the complicated sedimentation problem and different environmental conditions, no comprehensive, precise, and (most important) economic method can be recommended (Masjedi and Zaker 1999).

A common method of sediment load estimation for reservoirs in Iran is the use of hydrometric stations measurements, which is called hydrometry. This method is based on the Fleming equation (Shafai Bejestan 1999):

$$Q_s = aQ_W{}^b \qquad (1)$$

where Q_s is sediment discharge rate (M/T, tons/day), Q_w is flow discharge rate (L^3/T , m^3/s), and a and b are sediment rating coefficient and exponent, respectively. By measuring flow discharge rates at two inlet and outlet hydrometric stations of reservoirs, sampling of the sediment particles, determining relative laboratory concentration, drawing different curves and doing related calculations, long-term amounts of water and sediment are determined (Masjedi and Zaker 1999). In other words, in the hydrography method, the net amount of sediment deposited in the reservoir must be measured, and to obtain that amount, the hydrometric method should be used. Thus all measurements should be carried out both downstream and upstream of the dam, and the difference between inlet and outlet sediments is the amount of sediment deposited in the reservoir, thereby reducing the capacity of the reservoir.

Shahidi (1995) estimated the sediment entering the dam reservoir in Khozestan Province using six hydrological methods and compared it with the actual amount of sediment deposited behind Dez Dam. Using equation (1) and correlating the average of the classes, he found that this method gave almost the same result as the actual measurement.

Akrami (1996) tested six hydrological methods for estimation of sediment in Dams of Latian (Tehran), Sefid Rood (Gilan), Esteghlal (Minab), Ekbatan (Hamadan), Mahabad (Western Azarbaijan), Dorodzan (Fars) and Dez (Khozestan) and found that the FAO method with classified data gave a closer result to sedimentation studies. Mutsvangwa (1999) studied sediment deposition for some dams in Zimbabwe using mathematical and experimental methods and concluded that experimental methods gave better results than mathematical methods. Horowitz (2002) estimated the Mississippi River suspended load using sediment rating curve. He found that for the best evaluation of annual sediment load in a 20-year period, sediment rating curves can be used.

In this research the annual suspended load in hydrometric stations of Seera and Beylaghan (inlet and outlet hydrometric stations of Karaj Dam) was estimated by using long-term hydrometric data (1961-2000) and the corrected form of equation (1) (Heidarnejad 2004). By calculating bed load and mean sediment, an estimation of total sediment load and volume of deposited sediment in Karaj Dam Reservoir was completed first, then trap efficiency and useful life of the dam were calculated. To compare the hydrometry and hydrography methods, the early (1961) and secondary (2001) area-volume curves were used.

Materials and Methods

The Amir Kabir Dam (Karaj) is located on the Karaj River in Varian Strait (51°5'E, 23°57'N; 23 km from the city of Karaj; Table 1). This is a storage and multi-purpose dam constructed for drinking water for Tehran, hydroelectric power production and agricultural irrigation of Karaj plain. In the lake behind the dam, recreational uses such as boating and skiing are also common.

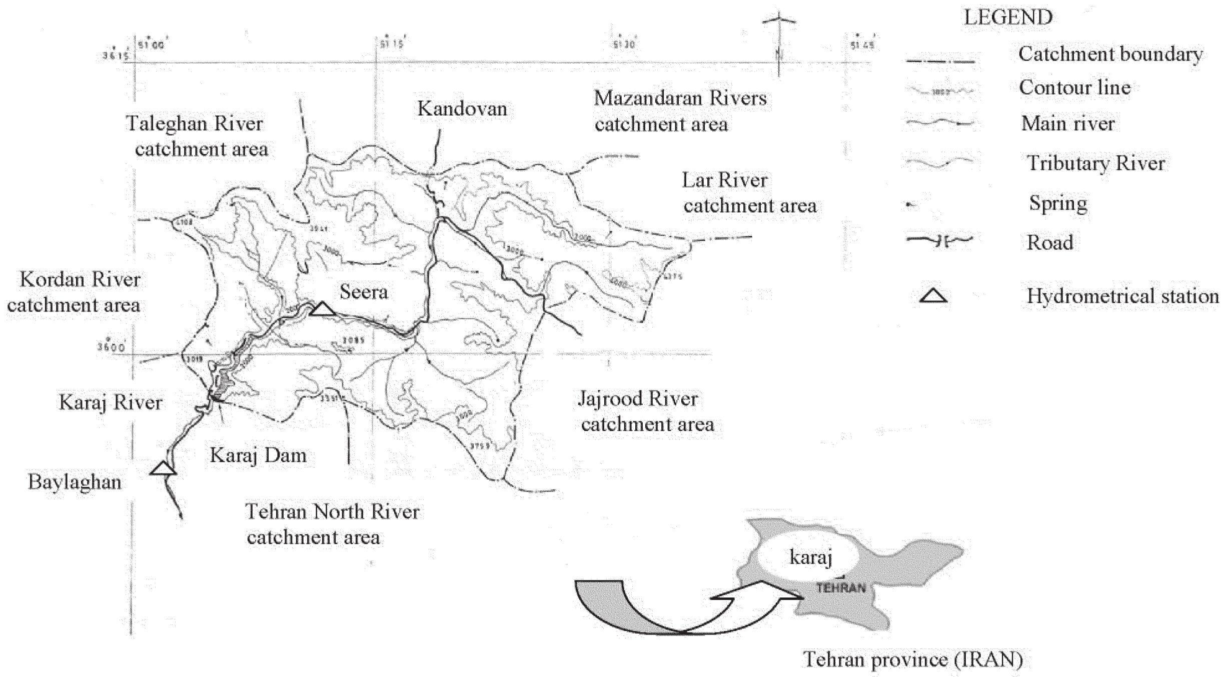

Figure 1.-Karaj catchment area.

The Karaj River watershed is located between 52°2' to 51°32'E and 35°52' to 36°11'N with an area of 850 km^2 and a circumference of 146 km on the southern slope of Mount Alborz. The area of the watershed at the inlet station of Seera is 720 km^2. The highest point of the watershed is about 4200 m and lowest point is at the location of the dam, 1600 m MSL. The watershed for Karaj Dam (Fig. 1) is bordered in the north by the watersheds of Mazandaran, Lar and Taleghan rivers and in the south, east and west by the watersheds of the Jajrood, Kardan, and northern Tehran rivers. The climate of the region is influenced by weather fronts from across the Mediterranean Sea. The river is 66.2 km, which enters the Karaj Dam in Seera location (Ministry of Power 1991).

To estimate the deposited sediment volume in the Karaj Dam reservoir, first the daily water and sediment discharge rates were determined. The Technical Hydrology (TH) software, an advanced edition of Smirnov Kolmogorov, was used to test homogeneity of the data (Rezaee 2001). This test is based on the comparison of the experimental distribution in two parts of a divided sample. The greatest difference between two functions for a known value of discharge rate, which is parallel to frequency axis (x-axis), is the maximum measured deviation of the two curves and is shown by the symbol D_{max}. The value of z is calculated from the following equation:

$$z = D_{\max}\sqrt{\frac{n_1 n_2}{n_1 + n_2}} \tag{2}$$

Where n_1 and n_2 are the elements of each divided section and z is the random variable innovated by the Smirnov, which is used for a similar population in the Kolmogorov distribution. The probability variable z is determined from the Kolmogorov distribution by the parameter l(z):

$$l(z) = p\left(D_{\max}\sqrt{n} < z\right) \tag{3}$$

Where *l(z)* is the probability that the maximum difference between statistical distribution functions in two samples from a population is not greater than z. This means that for random samples, the maximum deviation should be equal to or less than l(z) 100% or greater than [1-l(z)] 100% in the samples. The high level of significance of homogeneity test is 70 and the low level is 30. So, the data occurring in the following range are homogeneous:

$$[1-l(z)]\ 100>70 \tag{4}$$

The data will not be homogeneous if the following condition exists:

$$[1-l(z)]\ 100<30 \tag{5}$$

When the following condition exists, then the results of homogeneity test are suspicious and one can not have a precise conclusion:

Table 2.-Sediment rating equations in inlet and outlet stations of Karaj Dam(Seera and Beylaghan).

Time of flow measurement	Seera Hydrometric Station		Beylaghan Hydrometric Station	
	$Q_s = a\ Q_w^{\ b}$	r	$Q_s = a\ Q_w^{\ b}$	r
March	$0.5713\ Q_w^{2.3868}$	0.8019	$0.4738\ Q_w^{2.2310}$	0.7772
April	$0.067\ Q_w^{2.9398}$	0.8552	$0.9707\ Q_w^{1.8950}$	0.7063
May	$0.0095\ Q_w^{3.3723}$	0.8389	$0.1552\ Q_w^{2.2999}$	0.7890
June	$0.0270\ Q_w^{3.0209}$	0.7840	$0.9709\ Q_w^{1.5599}$	0.6364
July	$0.0213\ Q_w^{4.2318}$	0.7924	$0.0051\ Q_w^{3.5205}$	0.6825
August	$0.0202\ Q_w^{4.7733}$	0.7922	$0.00005\ Q_w^{5.2613}$	0.5144
September	$0.3816\ Q_w^{2.7239}$	0.9026	$0.0032\ Q_w^{3.8863}$	0.7233
October	$0.1300\ Q_w^{3.5192}$	0.8698	$0.0015\ Q_w^{4.2964}$	0.6302
November	$0.6019\ Q_w^{2.5402}$	0.7476	$0.0025\ Q_w^{4.4367}$	0.8315
December	$1.6311\ Q_w^{1.8373}$	0.8304	$0.6472\ Q_w^{2.1280}$	0.8439
January	$1.7675\ Q_w^{1.9004}$	0.6838	$0.5267\ Q_w^{2.2413}$	0.6631
February	$0.3933\ Q_w^{2.63894}$	0.8787	$0.0346\ Q_w^{3.3196}$	0.7326

r is the correlation coefficient

$$30 \leq [1\text{-}l(z)]\ 100 \leq 70 \qquad (6)$$

The water flow rate is usually considered the most important factor in sediment transport, but for a single discharge rate different sediment loads are measured, making other factors, including time of measurement, important for sediment transport.

The investigation at inlet and outlet hydrometric stations of Karaj Dam showed that the monthly model gives the best results (Table 2). The data were separated for different discharge rates, time of measurements. Mean of least squares errors were used to choose the best model (Heidarnejad 2004). With the sediment rating equations of the monthly models, the daily and annual sediment load was obtained for 30 years (1961-1991) and for the whole statistical period of 1961-2000. The 30-year results were for comparison of the results with the hydrographic model (primary and secondary area-volume curves of the dam). Because no suitable data were available on bed load in the Karaj River, the Karaushev experimental curve was used to determine the bed-to-suspended load ratios based on the slope of the river (Georgiev 1990). Studies showed that the Karaushev theory is applicable in Iranian rivers (Bahadori 2000).

The total sediment load was determined by addition of bed and suspended load. By dividing the sediment mass by the average density of the sediments, the volume of the sediment was obtained. Subtraction of inlet and outlet volume of sediments gave the volume of sediment deposited in the reservoir. The trap efficiency (T.E.) was calculated from the following equation (Tahershamsi and Sabzivand 1999):

$$T.E. = [\sum I_m - \sum O_m]\ 100\ /\ \sum I_m \qquad (7)$$

Where $\sum I_m$ is the total mineral sediments entering the reservoir of the dam and $\sum O_m$ is the total mineral sediments going out of the reservoir. Using the above equation and existing data of the inlet and outlet stations, the trap efficiency of the sediments were determined with sufficient accuracy. The useful life of the dam was determined so that 80% of the initial volume of the reservoir was full of sediments (Shafai Bejestan 1999).

Results and Discussion

The results of the homogeneity test show that the flow rate data were homogeneous at 91.2% level in Seera station and at 83% level at Beylaghan station (Fig. 2 and 3).

Considering daily flow rates and monthly discharge rating equations (Table 2) the amount of sediments were determined in two hydrometric stations of Seera and Beylaghan (Table 3). The bed-to-suspended load ratio was obtained as 2 and 0.45 for Seera and Beylaghan stations, respectively, using the Karaushev curve (Fig. 4). The bed load in both stations was calculated by multiplying the above ratios and the suspended load (Table 4).

Total sediment was obtained by addition of bed and suspended loads in both stations (Table 5). The volume of the sediment was calculated by dividing the sediment mass by the sediment density (1.4 tons /m^3 from Sediment Studying of Water Research Center of Iran) for both inlet and outlet stations (Table 6). The difference between inlet and outlet

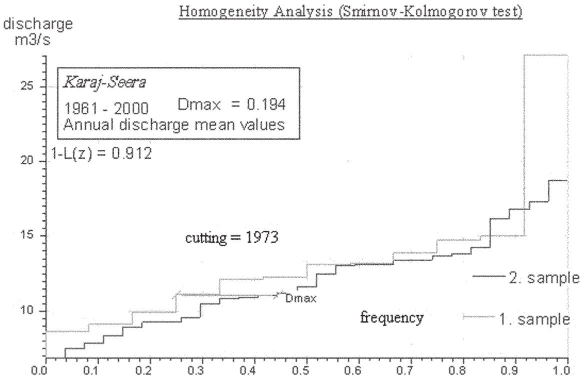

Figure 2.-The results of homogeneity test of water discharge rate data of Seera Station.

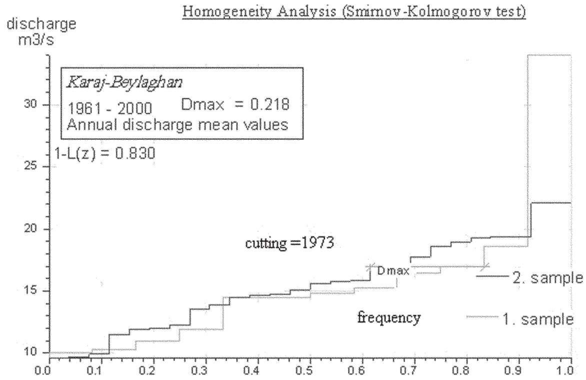

Figure 3.-The results of homogeneity tests of water discharge rate data of Beylaghan Station.

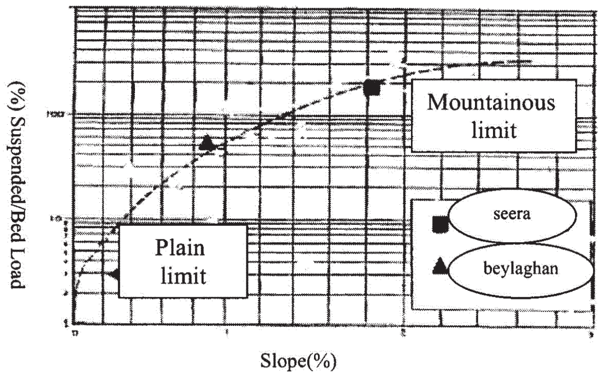

Figure 4.-Ratios of bed load to suspended load as a function of slope of Karaj River.

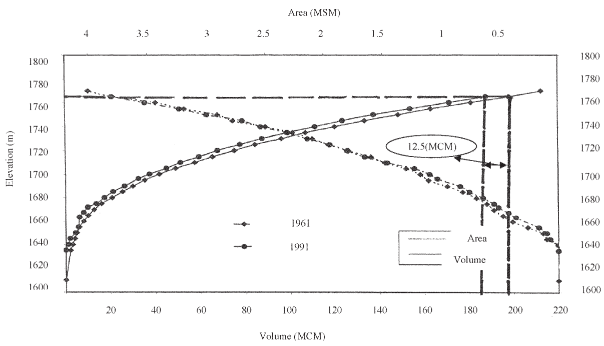

Figure 5.-The Volume-Elevation-Area Curve of Karaj Dam (Shabanloo 2000).

Table 3.-Estimated suspended sediment load in two stations of Seera and Beylaghan(tons).

Station	Suspended load (tons) for 1961-1991	Suspended load (tons) for 1961-2000
Seera	7452184.691	10500290.26
Beylaghan	3643386.409	4341892.043

Table 4.-Estimated bed sediment load in two stations of Seera and Beylaghan (tons).

Station	Bed/suspended Load ratio	Bed load (tons) for 1961-1991	Bed load (tons) for 1961-2000
Seera	2	1404369.38	21000580.52
Beylaghan	0.45	1639523.884	1953851.419

Table 5.-Estimated total sediment load in two stations of Seera and Beylaghan (tons).

Station	Total load (tons) for 1961-1991	Total load (tons) for 1961-2000
Seera	22356554.07	31500870.78
Beylaghan	5282910.293	6295743.462

Table 6.-Estimated sediment volume in two stations of Seera and Beylaghan(m^3).

Station	Sediment volume (m^3) for 1961-1991	Sediment volume (m^3) for 1961-2000
Seera	15968967.19	22500621.99
Beylaghan	3773507.352	4496959.616

sediment volumes, the deposited sediment volume for 1961-1991, was approximately 12,195,460 m^3 (compared to the hydrographic method) and 18,003,662 m^3 for 1961-2000. In comparison, from primary and secondary area-volume curves of Karaj Dam (Fig. 5), the deposited volume of sediment was 12,500,000 m^3 for 30 years of 1961-1991.

The average annual deposited sediment for the hydrographic method is 416,667 m^3 and for the hydrometry method is 406,515 m^3 in the same 30-year period.

To calculate the trap efficiency:

$\sum I_m$ = 31,500,870.78 tons, $\sum O_m$ = 6,295,743.462 tons, and T.E. = (31500870.78-6295743.462) 100/(31500870.462) = 80

The T.E. of Karaj dam was 80% for the period 1961-2000.

The deposited volume of sediment in the reservoir (lost capacity of the reservoir) was 18,003,662 m^3 during 1961-2000. So the annual lost capacity of the reservoir is 18003662/39 years = 461,632 m^3/year. Finally, if the useful capacity of the reservoir is 195 x 10^6 m^3, the useful life of the dam is calculated to be: 80% x 195 x 10^6/461632= 338 years.

Conclusions

This research and data analysis show that hydrometry and hydrography methods give almost the same deposited volume of sediments. The hydrography method resulted in 12.5 x 10^6 m^3 of lost capacity, whereas the hydrometry method gave 12.1 x 10^6 m^3 of lost capacity in the period of 1961-1991. The agreement is due to measurements of suspended and bed loads and use of the monthly sediment rating curve and Karaushev curve. The 3% difference is due to the method of bed-load approximation and employing an average value for density of the sediments. The T.E. of Karaj dam was 80%, which was close to the 77.92% of Tahershamsi and Sabzivand result (1999). The useful life of Karaj Dam was therefore 338 years based on hydrology and sedimentation. With annual sedimentation of 416,000 m^3, this useful life is quite acceptable and possibly greater than the structural life of the dam.

Karaj River has a low sedimentation problem with respect to other rivers of the country, and this helps explain the good drinking water quality for Tehran.

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