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Reservoir sedimentation in the Demirköprü Dam, Turkey

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ABSTRACT: The Demirköprü Reservoir is located on the Gediz River in West Central Turkey and has a storage capacity of 1.32x10^9 m^3 at Normal Water Surface Elevation. Construction of the dam was started in 1954 and completed in 1960. Sediment accumulation within the Demirköprü Reservoir influences the operation life of the dam. In the present study, reservoir sedimentation was assessed by two ways: comparison between successive hydrographic surveys and suspended sediment measurements. Since 1960, two hydrographic surveys were carried out at Demirköprü Reservoir, i.e., in 1977 and 1991. It is seen from the final measurement that 33% of the total storage volume of the reservoir was lost due to sediment deposition. There exists only one sediment gauging station in the drainage area of the Demirköprü Reservoir. The drainage area of the gauging station is about 50% of the total drainage area. In this study, the comparison of the two hydrographic maps together with the suspended sediment measurements is investigated thoroughly. Additionally, the sediment yield of the Demirköprü drainage area is estimated using both hydrographic and suspended sediment data. It is found that the sediment yield rate calculated from hydrographic surveys is almost 5.3 times that of the rate obtained from the suspended sediment measurements.

Keywords: Reservoir sedimentation, Demirköprü Dam, Suspended sediment measurement, Reservoir resurvey, Sediment yield

1 INTRODUCTION

Engineering projects involving reservoirs, from feasibility to the operation stages, necessitate reliable studies for evaluation and prediction of sediment distribution in the reservoir basins. All reservoirs formed by construction of dams on rivers are subject to the problem of sedimentation. A thorough knowledge of the reservoir sedimentation process, its evaluation, magnitude and effects, is essential for the ultimate success of the entire engineering project. The prediction of rate and formation of reservoir sedimentation with a sufficient accuracy is of interest to hydraulic engineers for a long time. The interest in general is due to the estimation of economic life of a reservoir in planning stage or prolonging at the existing one.

In Turkey, many reservoirs have lost their capacity rapidly as a result of high sedimentation rate, occurring mainly due to the change of land use and failure to take adequate measures to control soil erosion. The reservoir of the Demirköprü Dam is a typical example in Turkey encountering reservoir sedimentation problem. The Demirköprü Dam, located on the Gediz River in the west of Turkey, was constructed between 1954 and 1960 to irrigate the Gediz Plain, to control floods, and to generate hydropower energy. The dam has a drainage area of about 6590 km^2 in extend as shown in Figure 1. The original storage capacity is 1.32 km^3 at the Normal Water Surface Elevation (NWSE) of 244.2 m above sea level. The reservoir, 18 km long, was formed by a 74 m high earth-fill embankment dam.

Analysis of the sedimentation problem in the Demirköprü Dam reservoir was investigated by evaluating hydrographic surveys. In the present study, the amount of reservoir sedimentation in the Demirköprü Dam is calculated from the comparison of two successive hydrographic surveys executed in 1977 and 1991. The Sediment Yield Rate (SYR) values calculated from hydrographic surveys and suspended sediment measurements are also compared in this context.

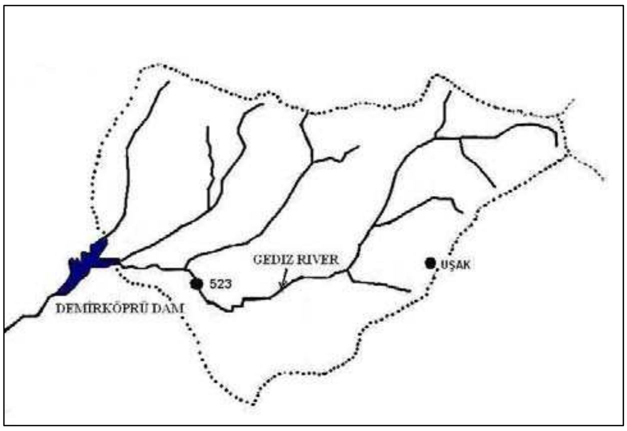

Figure 1. Drainage Area of the Gediz River and location of Sediment gauging station 523

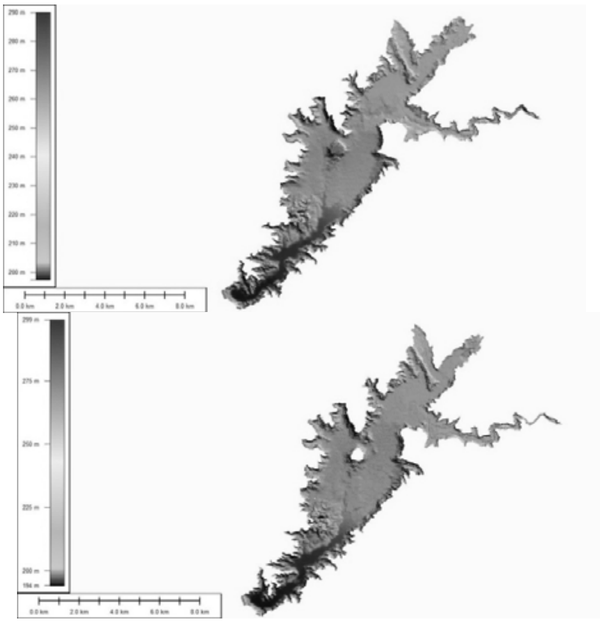

Figure 2. Images of hydrographic surveys; a) 1977, b) 1991

2 ANALYSIS OF RESERVOIR SEDIMENTATION IN THE DEMIRKÖPRÜ DAM

2.1 *Reservoir surveys and loss of reservoir capacity*

The primary objective of a reservoir survey is to measure the current reservoir area and capacity. The main cause of storage change is sediment deposition. Typical results from reservoir survey data collection and analysis include measured sediment deposition since dam closure and previous surveys, sediment yield from the contributing drainage, and future storage-depletion trends. Survey results can also include location of deposited sediment (lateral and longitudinal distribution), sediment density, reservoir trap efficiency, and evolution of project operation (Erosion and Sedimentation Manual, 2006).

Two reservoir capacity surveys were carried out in the Demirköprü Dam reservoir in 1977 and 1991, respectively. Figure 2 shows two images of hydrographic maps based on these survey data. Digital Elevation Models (DEMs) used in the computation of the reservoir surface area and reservoir volume are obtained from these two hydrographic maps. Depending on the hydrographic surveys, elevation versus reservoir area and elevation versus reservoir volume values are plotted above the water surface elevation 230 on Figures 3 and 4, respectively.

As seen from Figure 3, the variation of reservoir water surface level (elevation) with surface area above and below the elevation 235 has a different tendency in years 1977 and 1991. Above elevation 235, the reservoir surface area in 1991 is larger than the area that of the year 1977. Possible reasons for this increase may be due to the combined effects of shoreline erosion, landslides and locally sediment accumulations at the reservoir upstream due to excessive reservoir water level variations, but their particular effects could not be predicted completely for the Demirköprü Dam reservoir.

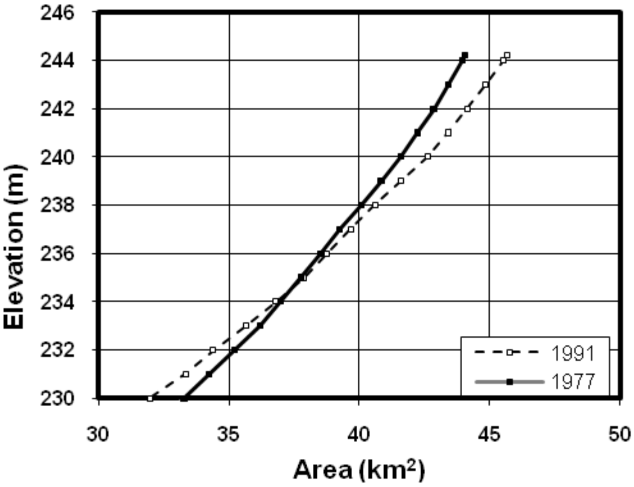

Figure 3. Variation of reservoir surface area with elevation

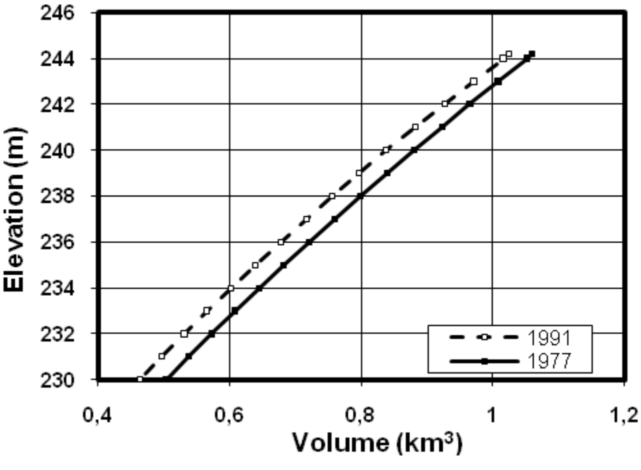

Figure 4. Variation of reservoir capacity with elevation

When the elevation-volume curve in Figure 4 is examined at the NWSE, it can be predicted that approximately 36 million cubic meters of the reservoir capacity was decreased from years 1977 to 1991. In other words, the reservoir was realized approximately 2.7% reduction in the capacity between 1977 and 1991.

Based on the value of the original reservoir capacity, calculations on the reservoir volume reduction can be done with using two successive hydrographic survey data. For this purpose, reservoir capacity loss versus operation year is plotted in Figure 5.

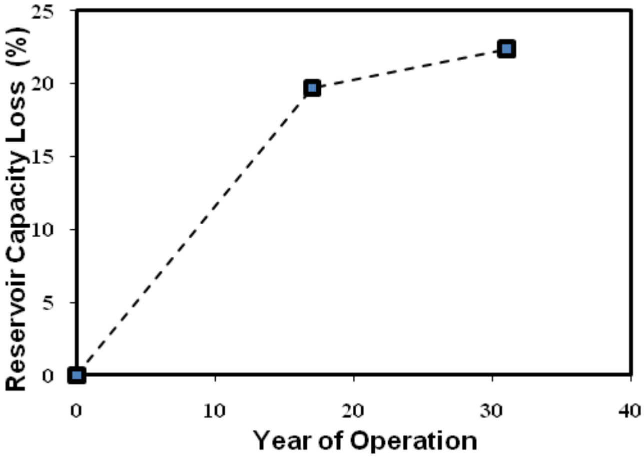

Figure 5. Reservoir capacity loss of the Demirköprü

At early periods of the reservoir operation, about 17 years of operation, the sedimentation rate in the reservoir shows a very rapid trend (i.e. about 1.15% per year). However, for the next 15 years of operation, the rate of sedimentation decreases remarkably to a value of 0.24% per year. Knowing that there is no upstream control of the Demirköprü Dam, technically it is difficult to explain about this 5 fold reduction in the sedimentation rate.

If the last survey value in 1991 compared with the original capacity value of 1.32 km^3, the total amount of volume reduction is calculated as 22.3% in 1991; i.e. the amount of volumetric reduction was 0.72% on annual basis. On the basis of this annual sedimentation rate, 36% of volume reduction may be expected in 2010.

2.2 *Trap efficiency*

The trap efficiency (T_E) of a reservoir is defined as the ratio of the volume of the deposited sediment (V_{dep}) to total sediment inflow (Q_{TS}), that is:

$$T_E=V_{dep}/Q_{TS} \quad (1)$$

One of the most popular methods to determine the trap efficiency of reservoirs was developed by Brune (1953) assuming that the trap efficiency depends only on the capacity-inflow (mean annual runoff) ratio:

$$T_E=f(V_{res}/Q_{inflow}) \quad (2)$$

where V_{res} is the initial reservoir storage capacity and Q_{inflow} is the mean annual inflow. The median Brune curve can be approximated as a series of logarithmic equations for $V_{res}/Q_{inflow}< 1$, if not

$$T_E=97.5\ \%\ \text{for}\ V_{res}/Q_{inflow} \geq 1 \quad (3)$$

In order to determine the trap efficiency of the Demirköprü Dam, first of all, the mean annual inflow of the Gediz River is calculated by using the monthly inflow data. The mean annual inflow is calculated as 708×10^6 m^3 for the time period of 1971 to 1999 based on the hydrologic data. Consequently, with this interpretation, the ratio of reservoir capacity to average annual inflow is found to be 1.86 for the original reservoir capacity of 1.32 km^3. The trap efficiency value is found to be 97.5% from the Brune Curve.

2.3 *Formation of Deposits in the Reservoir*

In order to find out the formation of delta deposits in the reservoir, the bottom profile passing through the centerline of the reservoir is drawn from the DEM data based on the hydrographic surveys conducted in 1977 and 1991 as shown in Figure 6. With the comparison of these two hydrographic surveys, two types of deposition pattern can be clearly observed from the bottom profile; i.e. bottom-set deposits and delta deposits.

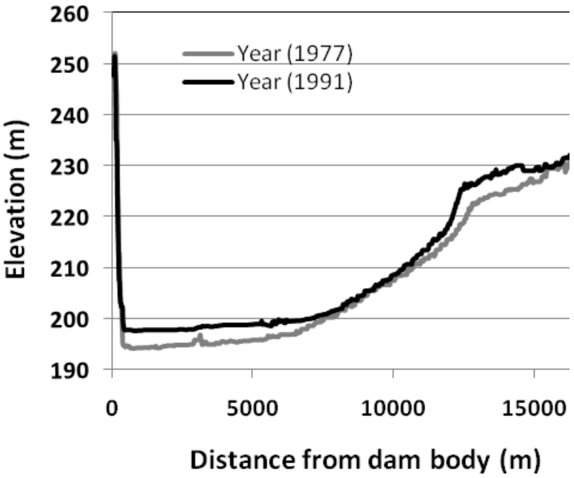

Figure 6. The profile of delta formation along the reservoir axis

The bottom-set deposits are developed in the main body of the reservoir basin and close to the dam as well, and built-up from fine and very fine suspended sediment transported by turbulent suspensions and by turbidity currents when they occur, and are deposited in quiescent water. In the case of Demirköprü Dam reservoir, according to the hydrographic survey data of 1977, the slope of the bottom-set deposits next to the dam is approximately equal to 4.14×10^{-4}. However, in 1991, the slope of the bottom-set deposits next to the dam body becomes nearly horizontal and reduced to a value of $3.40x10^{-4}$. In addition, within this period approximate increase in the bed level just upstream of the dam body due to the fine sediment deposits is 3.2 m in total, i.e. 0.23 m increase per year.

The bed-load transported in the Gediz River, which is the coarse-grained particles, begin to deposit immediately at the head reaches of backwater. This is due to an increase in the depth and the cross-sectional area of the flow which results in a reduction of velocity, and thus, in the sediment transport capacity. This deposition continues along the reservoir until a section where the velocity becomes too small to maintain any transportation. The result is the formation of a delta as given in Fig. 6. It is clearly seen that at the upstream region of the reservoir, a deltaic-shaped deposit formation exists in the reservoir which is a typical non-uniform two-phase inflow case into shallow reservoirs. The topset slopes of the deltaic deposit formations can be determined as $1.99x10^{-3}$ for 1977 and $1.36x10^{-3}$ for 1991, respectively. Similarly, the foreset slopes formed at the head of the delta formation have been found to be $8.93x10^{-3}$ for 1977 and $1.36x10^{-2}$ for 1991, respectively. The ratios of the foreset slope to the-topset slope are calculated as 4.48 and 10 for years 1977 and 1991, respectively. Borland (1971) found that the average foreset slope is 6.5 times the topset slope in the reservoirs of United States. However, Smith et al. (1964) reported that some steeper slopes have been observed, where the measured foreset slope of delta was 100 times the topset slope (Batuca and Jordaan, 2000). Therefore, it may vary from one reservoir to another. For example, Kokpinar et al. (2008) found the ratio of the foreset to topset slope as 37.9 at the Seyhan Dam reservoir in Turkey.

The separation between the topset and foreset deposits occurs by virtue of a pivot point at a location which depends primarily on the reservoir operation and on the existing channel slope in the delta area. The pivot points at the delta of the Demirköprü Dam deposits in years 1977 and 1991 are clearly seen in Figure 6. Referring to this figure one can conclude that the progress speed of the delta towards the dam body is 25 m/year in the Demirköprü Dam reservoir between 1977 and 1991. However, Batuca and Jordaan (2000) noted that depending on the reservoir hydrology, hydraulics, sediment transport, size and configuration, the speed of progress of the delta is variable from 50 to 200 m per annum.

In Figure 7, Section 1-1 (indicated in Fig.2) is given to show the cross-sectional change in the lateral direction of the reservoir between 1977 and 1991. This section also indicates the encountering region of the Gediz River to the reservoir lake and shows morphological changes of the region (see the image showing the region in Figure 8). Even it is expected that sediment deposition is initially focused in the deepest part of the cross-section, creating deposits having a near-horizontal surface regardless of the original section shape; this is not the case for Section 1-1. This is actually due to locally sediment inflow from the Gediz River and channel erosion during drawdown in dry seasons. Therefore, it is clearly observed from Figure 7 that while the cross sectional shape in 1977 is almost horizontal, in 1991 the central part is scoured forming a main channel with deposited sediments at the banks of the channel.

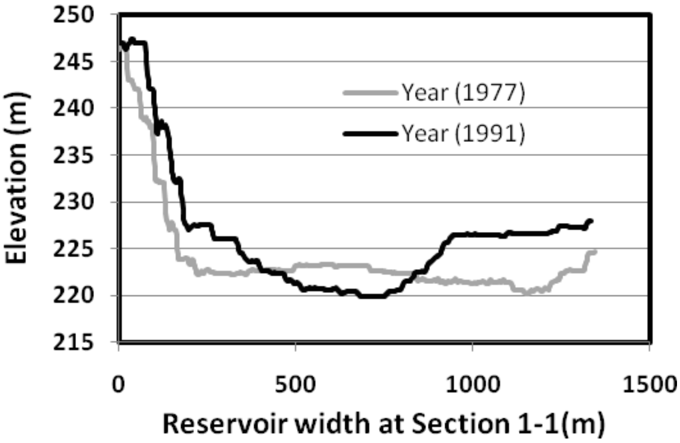

Figure 7. Cross-sectional change at Section 1-1 from 1971 to 1999, showing the deposition of sediment in the transverse direction

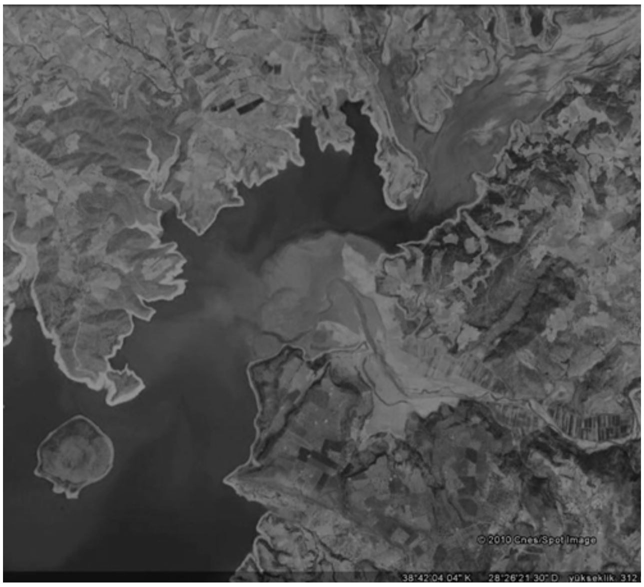

Figure 8. Image showing delta front taken at dry season of the reservoir water level (source: Google Earth© 2010)

3 SUSPENDED SEDIMENT MEASUREMENTS

The earliest and very limited sediment measurements on the Gediz River were made in the planning stage of the Demirköprü Dam Project. Before this date, no measurements of sediment concentration were available in the Gediz River except for a single series at a gauging station during February 1941. Even though these measurements showed a sediment concentration of 2% to 4.5 % by volume, it was considered that these values did not indicate the average concentration. Therefore, in the planning stage, a value of 0.5% was estimated to be representative of the sediment concentration of the average annual reservoir inflow of 22.4 m^3/s (annual inflow volume is $708x10^6$ m^3).

To construct a more comprehensive sediment budget for the Demirköprü Dam reservoir, the suspended sediment data that had been collected by the General Directorate of Electrical Power Resources Survey and Development Administration (EIE) between the periods of 1971 to 1984 for the gauging station 523 were used (EIE, 1987). Because of the location of this gauging station on the drainage area of the Gediz River (Figure 1), the measurements conducted at this station is important to get some information on the suspended sediment transport rate in the Gediz River. The hydrological characteristics of the gauging station 523 are given in Table 1. The drainage area of the station corresponds to 50% of the Gediz Dam drainage area, which gives representative hydrological characteristics for the whole drainage area. The suspended sediment samples taken at this gauging station was used to develop the sediment rating curves. The mean sediment concentrations were converted into tons per day of sediment load according to the instantaneous discharge. The sediment load was plotted against the instantaneous discharge on log-log scale and a straight line of power function was fitted by regression analysis as shown in Figure 9. The expression of the best fit line obtained from the data of the gauging station is in the following form with a correlation coefficient of $R^2=0.82$:

$$Q_s=4.08Q^{1.91} \quad (4)$$

where Q_s is the suspended sediment discharge in tons per day and Q is the instantaneous water discharge in the Gediz River in m^3/s. The total sediment load was computed by applying this rating curve to the mean discharges at the gauging station 532. Using this sediment rating curve, the suspended sediment part of the total sediment budget for this station was estimated. Since there were no bed-load measurements, it was estimated as 20% of the suspended sediment load (Morris and Fan, 1990).

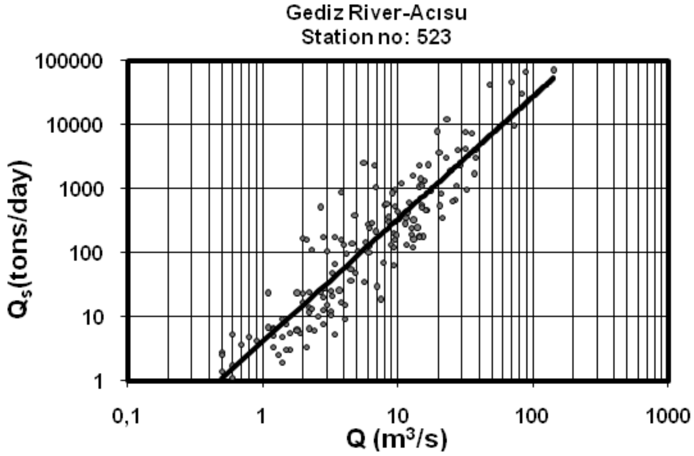

Figure 9. Variation of suspended sediment discharge with water discharge for gauging station 523

Table 1. Hydrological characteristics of gauging station 523

Station no	Drainage Area (km^2)	Mean annual discharge (m^3/s)
523	3228	12.76

4 SEDIMENT YIELD RATE OF THE DEMIRKÖPRÜ DAM DRAINAGE AREA

Sediment yield refers to the amount of sediment exported by a basin over a period of time, which is also the amount which will enter a reservoir located at the downstream limit of the basin. Sediment yield can be computed from reservoir surveys or a fluvial sediment monitoring program. Although both methods have potentially important sources of error, reservoir survey data generally represent a more reliable measure of long-term basin sediment yield (Morris and Fan, 1990).

In this part of the present study, by evaluating hydrographic surveys of the Demirköprü Dam reservoir, the comparison was made between sediment yield rates calculated using suspended sediment measurements and actual resurvey values.

Based on the hydrographic surveys in 1977 and 1991, annually deposited sediment volume is found from;

$$V_{dep}=(\Delta V)_{\Delta T}/\Delta T=(36x10^6)/14=2.57x10^6 \text{ m}^3/\text{year}$$

where V_{dep} is the annually deposited sediment volume, ΔV is the volumetric difference of sedimentation between two successive hydrographic surveys, and ΔT is the year difference between two successive hydrographic surveys.

Using this annual deposition volume, $V_{dep}=2.57x10^6$ m^3/year, the corresponding Sediment Yield Rate from the hydrographic surveys

$(SYR)_{HS}$ can be calculated with a drainage area A of 6590 km^2 as,

$(SYR)_{HS}= V_{dep}/A=389\ m^3/year/km^2$

On the other hand, using Eq. (4) and the mean annual inflow discharge, Q=22.4 m^3/s into the reservoir, the weight of the daily transported suspended sediment can be obtained as Q_s=1547.5 tons/day. On annual basis it will be, Q_s=564841 tons/year. When no field measurement data are available, US Soil Conservation Service recommended some design values for the 50 years' specific weight of deposited sediments (Batuca and Jordan, 2000). A value of 1400 kg/m^3 is accepted in this study, as nearly the average value of the mixture in equal parts of silt and sand. Including the bed-load to suspended sediment load as 20% of suspended load, then the volume of the deposited sediment can be estimated as, V_{dep}=484148 m^3/year. The corresponding Sediment Yield Rate from the suspended sediment measurements $(SYR)_{meas}$ can be calculated with a drainage area A of 6590 km^2 as,

$(SYR)_{meas}= V_{dep}/A=73.46\ m^3/year/km^2$

If one compares these two calculated SYR values, one from the hydrographic survey data, $(SYR)_{HS}$, and another from the suspended sediment measurements $(SYR)_{meas}$, it can be seen that $(SYR)_{HS}$ is almost five times higher than the $(SYR)_{meas}$ value. The difference is generally due to insufficient number of measurement records during flood flows when high amount of sediment transport occurs in the Gediz River. Another important point is the lack of bed-load measurements in the gauging station. Since bed-load generally constitutes significant part of the delta deposits as in the Demirköprü Dam reservoir, the approximation of taking the bed-load as 20% of the suspended sediment is suspicious and estimation of the bed-load is not highly reliable based on this assumption.

5 CONCLUSIONS

The following conclusions can be drawn from the results of this study:

1. The hydrographic surveys indicated that 36 percent of the total capacity of the Demirköprü Dam was lost within 50 years of the reservoir operation.
2. The forms of the delta deposits are investigated in detail. The topset slopes of the delta were calculated as $1.99x10^{-3}$ for 1977 and $1.36x10^{-3}$ for 1991, respectively. Foreset slopes of the delta were calculated as $8.93x10^{-3}$ for 1977 and $1.36x10^{-2}$ for 1991, respectively. The ratios of the foreset slope to the topset slope are calculated as 4.48 and 10 for years 1977 and 1991, respectively.
3. Depending on the last hydrographic survey data in 1991, it was measured that the distance between the pivot of the delta deposits and the dam body was about 12.5 km. It was observed that the delta deposit approaches towards the dam body with a speed of 25 m/year.
4. Both using deposited volumes obtained from the hydrographic survey data and suspended sediment measurement data obtained from the sampling station, SYR of the Gediz River Drainage Area was calculated as 389 $m^3/year/km^2$ and 73.46 $m^3/yr/km^2$, respectively. The difference between these two SYR values is expected mainly due to lack of insufficient number of measurements for suspended load and no bed-load measurements during flood events.

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