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Suspended Sediment Loads Through Flood Events for Streams of Sakarya River Basin

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Abstract

Most of the annual sediment yield from a watershed is transported by a stream during a small number of floods that occur in a relatively short period of time in a year. The aim of this article is to determine the possibilities of using only flood discharges for estimating transported suspended sediment loads to obtain easy and quick sediment load data for watershed conservation and reservoir planning studies.

In this study, the transported suspended sediment load during flood events is examined, and relations between the annual sediment yield and the sediment load during the major floods in a given year are developed based on available stream suspended sediment data from the Sakarya River basin in Turkey.

The importance of floods in the transport of a large percentage of annual sediment load can be illustrated very clearly by constructing cumulative sediment transport curves. In this study, for each station, cumulative sediment transport curves were determined.

A total of 45 regression equations were found to estimate annual transported suspended sediment loads using the highest annual flood, two highest annual floods, three highest annual floods, and until ten highest annual floods for subbasins of the Sakarya River basin. From among these equations, seven equations with the highest R^2 were proposed to estimate annual transported suspended sediment loads.

Key Words: Sakarya River basin, Suspended sediment, Flood-sediment relationship, Estimation of suspended sediment load, Cumulative transported sediment curve

Sakarya Havzasında Taşkınlarla Taşınan Asılı Sediment Miktarları

Özet

Bir su toplama havzasından akarsularla taşınan yıllık sediment miktarının büyük bir kısmı kısa bir zaman aralığında oluşan birkaç taşkın sırasında taşınır. Bu makalede, havza koruma ve rezervuar planlama çalışmalarında kullanmak üzere kolay ve çabuk veri elde etmek için taşınan asılı sediment miktarının tahmin edilmesinde sadece taşkın debilerinin kullanma olanaklarını belirlemek amaçlanmıştır. Çalışmada, Sakarya nehri havzasından elde edilmiş mevcut asılı sediment verileri ve taşkın debileri kullanılarak taşkın olayları sırasında taşınan asılı sediment miktarları incelenmiş, yıllık sediment miktarı ve o yıldaki önemli taşkınlar sırasında taşınan sediment miktarı arasında ilişkiler geliştirilmiştir.

Yıllık sediment miktarının önemli bir kısmının taşınmasında taşkınların önemi birikimli sediment taşıma eğrilerinin oluşturulması ile net bir şekilde gösterilebilir. Çalışmada her sediment gözlem istasyonu için birikimli taşınan asılı sediment eğrileri belirlenmiştir.

Çalışmada yıllık asılı sediment miktarının tahmin edilmesinde kullanılabilecek toplam 45 adet regresyon eşitliği, Sakarya havzasındaki alt havzalar için yıllık en büyük taşkın, yıllık en büyük iki taşkın ve yıllık en büyük 10 taşkına kadar kullanılarak elde edilmiştir. Bu eşitlikler arasından en büyük R^2'ye sahip yedi eşitlik, Sakarya havzasından taşınan yıllık asılı sediment miktarının tahmin edilmesinde kullanılmak üzere önerilmiştir.

Anahtar Sözcükler: Sakarya havzası, Asılı sediment, Taşkın-sediment ilişkisi, Asılı sediment miktarının tahmini, Birikimli taşınan sediment eğrisi

Introduction

The annual sediment load of a stream is an important factor for determining the dead storage volume of a dam. The annual sediment load of the stream is generally determined either from direct measurements of the sediment load throughout the year or from any of the many sediment transport equations that are available today. Direct measurement of the sediment load in a stream, which is the most reliable method, is very expensive and thus is not done for as many streams as the measurement of water discharge. On the other hand, most of the sediment transport equations require detailed information on the flow and sediment characteristics and generally do not agree with each other, making it difficult to choose the best equation for a given stream. Because of these problems researchers are always looking for simpler and easier methods to use relationships between sediment load and water discharge or drainage area of the stream. The most often utilised methods are based on relations between sediment load and water discharge. Even though there are reasonably good relations among the annual sediment load and the annual water discharge and drainage area, the spread of the data points used to develop those relations exceeds one log cycle. So it is possible to overestimate and underestimate the annual sediment load by a factor or more. One important consideration in annual sediment load measurements and calculations is the realisation that most of the annual sediment load is transported during flood events that take place over a relatively short time interval. Most studies have shown that a large percentage of the annual sediment load is generated by a small number of storms that occur every year. Storms were defined as follows: large storms are storms with a return period greater than two years; medium storms are storms with a return period from one to two years; and small storms: are storms with return a period less than one year (Piest, 1963).

Another important observation is the fact that not only do floods carry a large percentage of annual sediment load but also there is a very good relationship between the sediment load during floods and the annual sediment load (Demissie, 1996).

The aim of this article is to determine the possibilities of using only flood discharges for estimating transported suspended sediment loads to obtain easy and quick sediment data for watershed conservation and reservoir planning studies. The other aims are to find out the portion of transported suspended sediment loads during floods in the annual transported load, to estimate sediment load during the floods when only water discharge is measured but sediment data is not available, and to obtain annual sediment load with few daily sediment loads.

Materials and Methods

Materials

The Sakarya River basin area is 58 160 km^2 and covers 1/13 of the total area of Turkey. There are eight suspended sediment-gauging stations in the Sakarya River basin, which are shown in Figure 1 and Table 1 (Öztürk, 1997).

In the study, eight sediment-gauging stations in the Sakarya River basin with daily water and suspended sediment discharge data were used to develop the relations. The periods of suspended sediment and flow records of eight stations varied between 1962 and 1995. Both suspended sediment data and flow data are suitable for computing daily-suspended sediment load. So the Sakarya River basin was selected for the research area. Most of the same data that were analysed in (Öztürk, 1997) are also used in this study.

Methods

Distribution of suspended sediment load in a year

For each station, sediment loads of samples and discharges at sampling times were measured and their logarithms and the second and third power of these logarithms were calculated. After performing regression analysis, equations giving a non-negative estimation and with the highest R^2 and least variables were selected (Table 2). The General Directorate of Electrical Power Research Survey and Development Administration (EIE) also used this method.

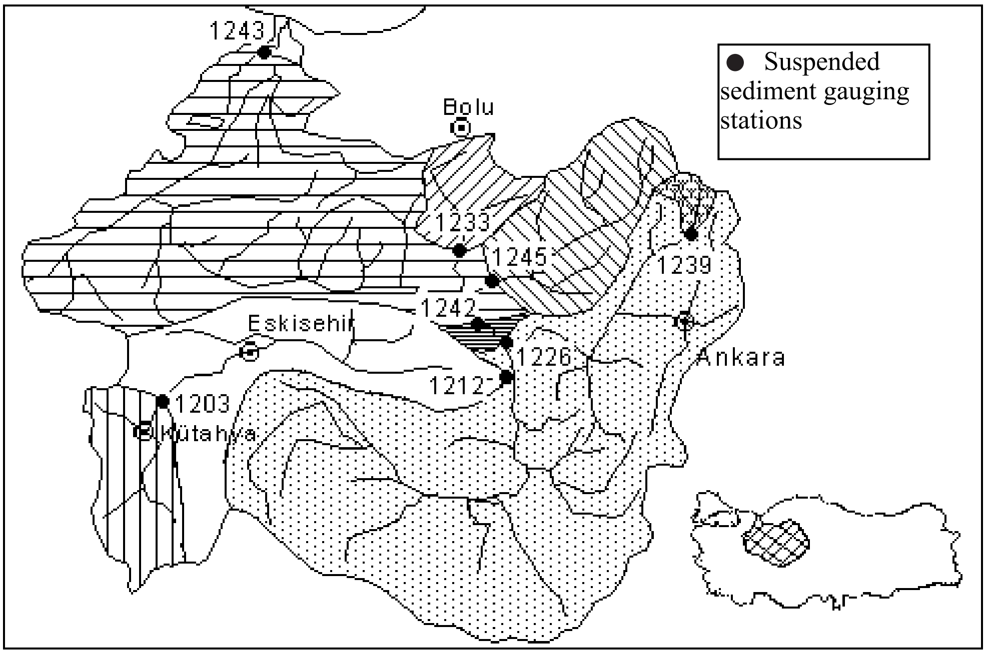

Figure 1. Suspended sediment gauging stations and their basin areas in the Sakarya River basin

Table 1. Gauging Stations Used in the Study in the Sakarya River Basin

Station Number	Station Name	Drainage Area, (km^2)	Period of Suspended Sediment Records	Average Discharge, (m^3/s)	Average Correlation Coefficient	Period of Flow Records
1203	Porsuk Creek Besdegirmen	3 938	1973-1995	9.07	0.914	1936-1995
1212	Porsuk Creek Sazilar	6 053	1977-1986	15.14	0.914	1944-1986
1226	Ankara Creek Mesecik	7 140	1967-1995	12.31	0.772	1963-1995
1233	Aladag Creek Karakoy	1 985	1963-1995	15.38	0.939	1958-1995
1239	Ova Creek Eybek	322	1967-1995	2.70	0.796	1956-1995
1242	Sakarya River Kargi	33 847	1963-1995	55.69	0.954	1961-1995
1243	Sakarya River Botbasi	55 322	1964-1992	183.80	0.935	1960-1992
1245	Kirmir Creek Taksir Bridge	3 942	1963-1992	17.57	0.971	1961-1992

Since discharge measurements were made more often during the sediment observation period for each month, the highest 10 water discharges were selected among average daily water discharges and 10 sediment load values were calculated by using regression equations. Then these sediment load values were ordered in descending order, and after performing regression analysis and making the necessary transformations, equations suitable for the above-mentioned criteria were selected.

The distribution of the suspended sediment load throughout the year was examined firstly for illustrating the importance of flood flows in the transport of suspended sediment. Generally it is expected that sediment load will be higher when the water discharge is high, because there is a good correlation between water discharge and sediment load. Correlation coefficients for daily-suspended sediment loads and water discharges were determined for the Sakarya River basin using a computer program.

Table 2. Equations Used in Suspended Sediment Load Estimation in the Sakarya River Basin

Station Number	Equations	Determination coefficient (R^2)
1203	Log Qs = 0.158 + 3.010 (Log Q) - 0.749 (Log Q)^2	0.774
1212	Log Qs = 0.597 + 0.897 (Log Q) + 0.588 (Log Q)^2	0.685
1226	Log Qs = 0.664 + 1.880 (Log Q)	0.820
1233	Log Qs = 0.588+ 1.210 (Log Q) + 0.155 (Log Q)^2	0.822
1239	Log Qs = 0.437 + 1.350 (Log Q) + 0.382 (Log Q)^2	0.812
1242	Log Qs = - 0.048 + 1.920 (Log Q)	0.714
1243	Log Qs = 1.870 - 0.264 (Log Q) + 0.497 (Log Q)^2	0.657
1245	Log Qs = 0.663 + 0.892 (Log Q) + 0.269 (Log Q)^2	0.844

Cumulative sediment transport curves

Ranking the daily sediment loads first, and then calculating the cumulative sum from the peak sediment load to the lowest in any year constructed the curves. The sediment loads and the time were then divided by the annual sediment load and total number of days in a year, respectively, to obtain percentage sediment load and percentage time by dividing by the annual sediment load and the total number of days in a year, respectively.

Relations between annual sediment load and sediment load through flood events

The annual water discharge hydrograph was first examined to identify the highest, the second highest, the third highest and if available until the tenth highest floods in any particular year. Then the total sediment discharge during those floods was calculated by summing up the daily sediment discharges during the flood periods. The water discharge values were not examined in station 1242 because of close discharge values. For this reason total sediment discharges were not calculated during floods.

Results and Conclusions

It was found that there is a good correlation between daily water discharge and sediment load for the Sakarya River subbasins. The correlation coefficients between the average daily sediment load and the water discharge for the Sakarya River subbasins based on long term data are shown in Table 1.

Distribution of suspended sediment load in a year

Average ratios of average monthly-suspended sediment load to total annual suspended sediment loads based on observation periods of each station are given in Table 3.

It can be seen from Table 3 that monthly sediment load percentages based on average annual sediment loads vary between 0.08 and 38.21. When we examine the variation of average transported suspended sediment loads in the Sakarya River basin based on seasons, the percentages are as follows: 54.6% for spring, 26.8% for winter, 10.8% for autumn, and 7.8% for summer. According to these results, sediment transportation from the Sakarya River basin is highest in spring, which has higher rates of precipitation and flow than the other seasons.

Among the gauging stations, station number 1239 has the maximum and minimum ratio of monthly-suspended sediment load. For the abovementioned station, in 1974, 97.2% (38 532.7 tons) of total suspended sediment load (39 651.6 tons) was transported in March (Öztürk, 1997). In other words, 118.9 tons of suspended sediment was transported through the other 11 months. For the same station, transported suspended sediment loads were taken as 0.0 for periods when the discharges of flows become 0.0.

Table 3. Monthly Minimum, and Maximum Suspended Sediment Loads, and Average Distribution of Suspended Sediment Load in a Year in the Sakarya River Basin, (%)

St. No	Water year	Months												Total
		10	11	12	1	2	3	4	5	6	7	8	9	
1203	Ave.	2.66	3.25	7.21	11.94	14.72	19.15	16.49	12.07	6.58	2.52	1.59	1.80	100
	Min.	0.89	1.18	2.30	4.22	8.09	10.94	7.39	3.68	1.40	0.68	0.46	0.37	-
	Max.	6.85	15.61	19.87	21.76	27.58	28.94	36.50	19.55	12.25	4.74	3.54	2.91	-
1212	Ave.	14.14	10.12	6.60	6.86	9.30	10.90	11.26	6.44	5.33	4.71	4.15	10.20	100
	Min.	3.87	2.91	1.52	2.25	2.98	4.57	3.72	1.77	2.30	1.52	2.47	3.48	-
	Max.	28.90	27.39	13.14	21.46	24.79	28.47	33.28	13.05	8.32	7.68	8.39	26.49	-
1226	Ave.	2.50	3.76	6.44	7.23	12.43	24.34	21.22	14.07	4.81	1.46	0.66	1.07	100
	Min.	0.10	0.17	0.32	0.87	1.33	9.61	3.77	1.59	0.57	0.16	0.05	0.10	-
	Max.	14.89	13.11	25.94	21.32	51.95	75.38	44.43	69.90	18.22	14.55	2.95	3.06	-
1233	Ave.	1.54	1.28	6.29	6.13	9.20	31.00	30.63	10.07	2.92	0.44	0.10	0.39	100
	Min.	0.10	0.12	0.26	0.25	0.33	5.62	2.88	0.38	0.19	0.02	0.01	0.01	-
	Max.	29.91	9.56	37.43	32.32	33.06	55.19	76.48	46.27	15.08	3.63	0.85	4.36	-
1239	Ave.	0.61	0.93	7.62	2.50	6.75	38.21	34.21	5.58	1.90	0.41	1.21	0.08	100
	Min.	0.01	0.04	0.04	0.03	0.06	0.97	0.66	0.92	0.08	0.01	0.00	0.00	-
	Max.	6.44	7.78	90.20	25.57	36.95	97.18	94.83	36.51	10.19	4.78	29.68	0.58	-
1242	Ave.	6.46	7.37	8.93	10.09	12.04	16.18	14.21	10.05	5.88	2.82	2.31	3.65	100
	Min.	1.14	1.49	3.58	4.74	6.19	9.29	4.81	3.48	2.48	1.39	1.15	1.09	-
	Max.	12.69	15.62	14.07	15.72	26.18	36.90	25.86	33.81	10.49	5.85	3.76	7.14	-
1243	Ave.	4.29	5.02	9.25	11.28	12.48	18.91	17.96	8.71	4.71	2.68	2.34	2.38	100
	Min.	1.17	1.10	3.22	5.34	4.95	8.05	2.43	2.35	1.31	0.79	0.49	0.41	-
	Max.	15.31	21.19	29.38	23.32	22.40	34.01	37.86	24.32	25.54	8.94	10.77	5.22	-
1245	Ave.	0.95	1.76	9.75	7.36	11.84	31.75	26.63	7.03	2.18	0.31	0.20	0.24	100
	Min.	0.09	0.14	0.20	0.39	0.29	6.17	2.98	1.21	0.13	0.03	0.02	0.02	-
	Max.	11.14	15.21	63.71	41.85	45.62	72.35	68.34	40.68	13.05	1.87	2.19	1.27	-
Basin Ave.		4.14	4.19	7.76	7.92	11.10	23.81	21.58	9.25	4.29	1.92	1.57	2.48	100

Cumulative sediment transport

The importance of floods in the transport of a large percentage of annual sediment load can be illustrated very clearly by constructing cumulative sediment transport curves (Demissie et al., 1986). This is shown in Figures 2 and 3 for the Sakarya River subbasins.

The percentage of annual suspended sediment load was obtained by calculating the ratio of transported sediment load to annual transported sediment load. The time percentage, which is the abscissa axis of cumulative sediment transport curves, was obtained by calculating the ratio of sediment transport time to number of days in a year.

The general form of the cumulative sediment transport curves will be similar for any stream (Figure 2 and 3). The main difference in the curves from stream to stream and year to year is the slope of the curves in the initial stages. These differences are caused by differences in the sediment carrying characteristics of the streams and the variability of the flow in a year and from year to year. Generally the curves are steeper for very dry years with very few floods than for wet years with a lot of flood events (Figure 2). Figure 2 shows that 99.0, 97.5 and 95.4 percent of the annual sediment load was transported in only 15 percent of the total time in 1974, 1992 and 1982. This is because few floods occur during dry years and carry most of the annual sediment load. For example, in 1974 there was only one flood for 12 days and it transported nearly the entire annual sediment load. In that year the peak water discharge was 81.5 m^3/s, average discharge was 6.30 m^3/s at the station 1239 (Öztürk, 1997). During wet years the steepness of the curves depends on the number of flood events and on the relative magnitudes of the floods with respect to each other. If the annual flood is much higher than the rest of the floods, the cumulative sediment transport curve will be expected to be very steep, indicating the significance of the annual flood in transporting a relatively high percentage of the annual sediment load (Figure 2). On the other hand, if the relative magnitudes of several floods are similar, then the slope of the cumulative transport curve is expected to be mild, indicating the contribution of several floods in transporting their share of the annual sediment load (Figure 3).

Suspended sediment transport curves of average values of period of suspended sediment records for subbasins of Sakarya River are shown in Figure 4. Figure 4 shows that the suspended sediment transport curves of average values for station 1239 are the steepest for the initial stage.

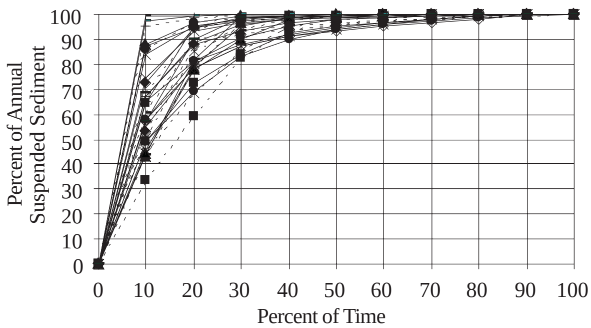

Figure 2. Cumulative sediment transport curves for gauging station 1239

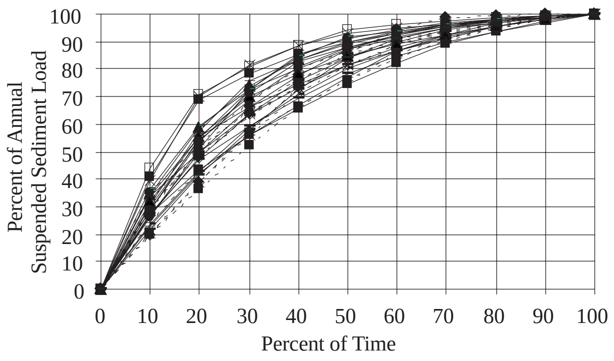

Figure 3. Cumulative sediment transport curves for gauging station 1243

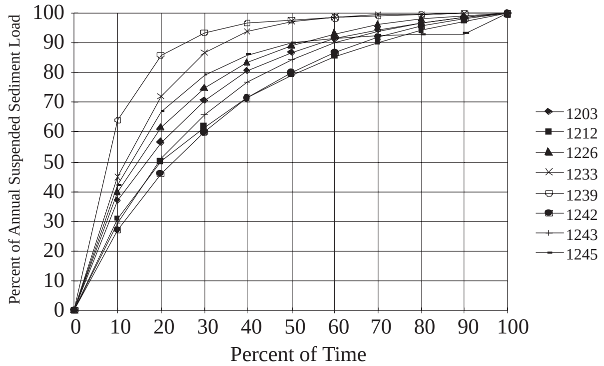

Figure 4. Suspended sediment transport curves of average values of period of suspended sediment records for subbasins of Sakarya River

In the Kankakee River basin in Illinois-USA, four years of data from four gauging stations showed that 50% of the annual sediment load was transported in only 4 to 53 days of the year (Demissie, 1986).

In the Sakarya River basin (station 1239), 65.4% of the annual suspended sediment load was transported in only one day of the year, from 65.5% to 94.4% of the annual load was transported in one to eight days of the year, and 97.2% of the annual load was transported in 31 days of the year (Öztürk, 1997).

Relations between annual sediment load and sediment load during flood events

The relations between the sediment load during annual floods and the annual sediment loads for seven gauging stations are obtained. A total of 45 regression equations were found to estimate annual transported suspended sediment loads using the highest annual flood, two highest annual floods, three highest annual floods, and until ten highest annual floods for subbasins of the Sakarya River basin. From among these equations, seven equations with the highest R^2 were proposed to estimate annual transported suspended sediment loads (Table 4). In the equations that are given in the Table 4, Qsa is annual sediment load in tons, Qs1 is sediment load during the highest flood in tons, Qs2 is sediment load during the two highest floods in tons, and parallel to the others Qs10 is sediment load during the ten highest floods in tons.

Table 4. Selected Relations Between the Sediment Load During Floods and the Annual Sediment Loads

Station Number	Degree of the Highest Floods	Equation	R^2 (%)
1203	4	Log Qsa = 1.720 + 0.7030 Log Qs4	97.2
1212	5	Log Qsa = 3.071 + 0.3507 Log Qs5 + 0.0184 (Log Qs5)^2	84.8
1226	6	Log Qsa = 6.524 – 1.1220 Log Qs6 + 0.1743 (Log Qs6)^2	90.8
1233	10	Log Qsa = 6.561 – 1.5070 Log Qs10 + 0.2418 (Log Qs10)^2	98.1
1239	4	Log Qsa = 0.8189 + 0.8559 Log Qs4	97.4
1243	8	Log Qsa = 13.230 – 2.7690 Log Qs8 + 0.2733 (Log Qs8)^2	85.6
1245	8	Log Qsa = 4.168 – 0.4916 Log Qs8 + 0.1372 (Log Qs8)^2	97.1

When the sediment transport during the highest flood is considered, generally there is a good correlation between the annual sediment load and the sediment load during the flood, except station 1212 and station 1233, because correlation coefficients generally must be greater than 60% in hydrology (Bayazit, 1991). The square of the correlation coefficient is also frequently used as a goodness of fit statistic because it (R^2) represents the fraction of the variation in the dependent variable that is explained by variation in the independent variables (McCuen and Snyder, 1985).

When the sediment transport during the two highest floods is considered, the correlation between the annual sediment load and the sediment load during the floods is better than that obtained using only the highest annual flood.

Further improvements in the relation between the annual sediment load and the sediment load during a flood event is achieved if the third to tenth highest floods are included.

The drainage areas of the gauging stations used in this study range from 322 to 55 322 km^2. Separating stations into subgroups can reduce the scatter of the data points in Figure 5. Stations were separated into three groups based on drainage area sizes and average water discharges (Table 5).

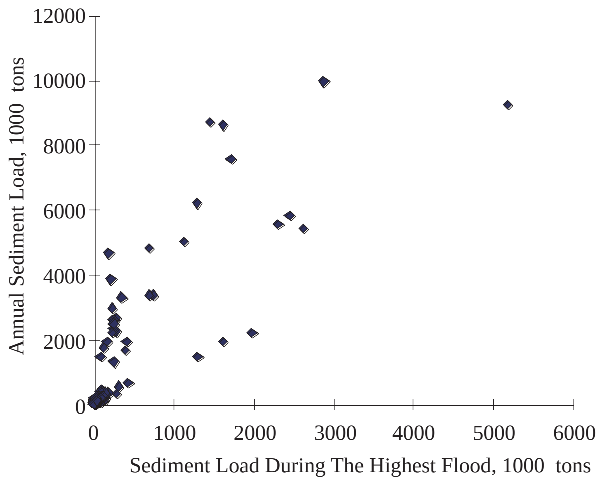

Figure 5. Annual sediment load versus the sediment load during the highest flood

The relations between the sediment load during annual floods and the annual sediment loads for subgroups are shown in Table 6.

However, there is not a considerable difference among the R^2 values of the equations (Tables 4 and 6).

Table 5. Subgroups of Suspended Sediment Gauging Stations

Group	Drainage Area (km^2)	Average Water Discharge (m^3/s)
First Group (1239)	322	2.70
Second Group (1203, 1212,1226, 1233 and 1245)	1985 - 7140	9.07 - 17.57
Third Group (1243)	55322	183.80

Table 6. The Relations Between the Sediment Load During Annual Floods and the Annual Sediment Loads for Sub-Groups

Sub-Group	Equation	R^2 (%)
First	$\text{Log Qsa} = 0.9924 + 0.7625 \text{ Log Qs4} + 0.0098 (\text{Log Qs4})^2$	97.4
Second	$\text{Log Qsa} = 3.9401 - 0.2583 \text{ Log Qs5} + 0.10174 (\text{Log Qs5})^2$	89.7
Third	$\text{Log Qsa} = 13.23 - 2.769 \text{ Log Qs8} + 0.2733 (\text{Log Qs8})^2$	85.6

Conclusions

Most of the annual suspended sediment load is transported during a few floods in a year. As an average the highest annual flood transports from 18.6 to 50.3 percent of the annual sediment load. Two highest annual floods transport from 27.1 to 64.0 percent of the annual sediment load. Three highest annual floods transport from 32.1 to 69.5 percent of the annual sediment load. Four highest annual floods transport from 35.5 to 71.5 percent of the annual sediment load. Five highest annual floods transport from 37.2 to 76.7 percent of the annual sediment load. The percentage of the annual sediment load transported by floods increases as the drainage area of the watershed decreases.

In this study, stations were separated into three groups according to drainage area sizes and average water discharges. But there is no considerable difference among the R^2 values of the equations.

Good correlations exist between the annual sediment load and the sediment load during the floods. The existence of very good correlations between the annual sediment load and the sediment load during a few floods should influence the strategy for sediment yield monitoring programs and the procedures for calculating the highest annual sediment loads of streams. For example, the development of equations related to annual sediment load and the sediment load during the annual flood could provide a simple procedure for estimating the annual sediment yield based on the sediment load during the highest annual flood. Such a procedure can result in a significant saving of effort and money for agencies responsible for monitoring and evaluating watershed erosion, reservoir sedimentation and conservation practices. It could also serve as an important tool in project design of reservoirs where limited or no sediment data are available. These relations provide good guidelines for sediment monitoring programs and also simple procedures for estimating annual sediment loads.

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