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Sediment and water discharge rates of Turkish Black Sea rivers before and after hydropower dam construction

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Abstract Presently, the water discharge rate to the Black Sea by Turkish rivers is approximately 41 km^3/yr. The sediment discharge rate of Turkish rivers to the Black Sea is 28×10^6 t/yr. Before construction of the hydroelectric dams, the sediment discharge rate was approximately 70×10^6 t/yr. The sharp reduction in sediment load is largely a result of the dams near the mouths of the Yesil Irmak and Kizil Irmak rivers. Before the construction of dams, Turkish rivers contributed approximately one third of the total amount of sediment received by the Black Sea from all surrounding rivers. The life-span of the major reservoirs varies from approximately only one century (Yesil Irmak river reservoirs) to several thousand years (Sakarya river reservoirs). Life-span for the large Altinkaya Dam reservoir is estimated with approximately 500 yr.

Key words Discharge — River — Turkey — Black Sea — Sediment load — Dam — Reservoir — Siltation — Sediment yield — Runoff — Anatolian Mountains

Introduction

The Black Sea represents a large catch basin for the river discharge from large areas of southeastern Europe, the Caucasian Mountains, and from northern Turkey. While river discharge rates from the European and Caucasian rivers were studied previously, the sediment and water discharge rates by all Turkish rivers discharging into the Black Sea had not been well established. This was partly related to the great number of smaller rivers along the Turkish coast.

The main purpose of this paper was to establish the total discharge rates of water and sediment to the Black Sea for Turkish rivers at present and before the construction of hydroelectric dams. Water discharge rates to the Black Sea provide useful information for mass balance calculations of the sensitive Black Sea environment, which is characterized by anoxic conditions below a depth of only approximately 100 m (e.g., Codispoti and others 1991). Sediment discharge data provide useful information for the interpretation of the recent sediment record in the Black Sea.

The understanding of both discharge rates is useful also for the effective management of Turkey's water resources such as hydroelectric energy generation, irrigation, and drinking water supply. As part of the increasing utilization of the considerable water resources in Turkey, a systematic data collection and sampling program was established by the Electrical Resources Survey Administration of Turkey (EIE) in 1962. A network of stream gaging stations was set up across the country. Monthy data collected up to 1984 were published in EIE (1987).

The sediment discharge rates allowed first-order life-span estimates for some of the major reservoirs along the rivers. The life-span is defined as the time period that it takes to fill the reservoir behind a hydroelectric dam with sediment transported in by the river.

Physiographic setting

The physiography of Turkey is marked by the central Anatolian plateau with an altitude of, on average, 1100 m. The elevation of the plateau increases to the east. The Black Sea is separated from this plateau by two chains of North Anatolian mountains (Pontic Mountains): the lower Giresun Daglari in the center and the higher Dogu Karadeniz Daglari in the east. Northern Turkey is tectonically active and cut by several fault lines, such as the Northern Anatolian Fault. As a result, the mountains slopes are steep. The five major Turkish rivers draining into the Black Sea are the Sakarya, Filyos, Kizil Irmak, Yesil Irmak, and Coruh (Fig. 1). A large number of smaller rivers drain the steep slopes along the coastal mountains.

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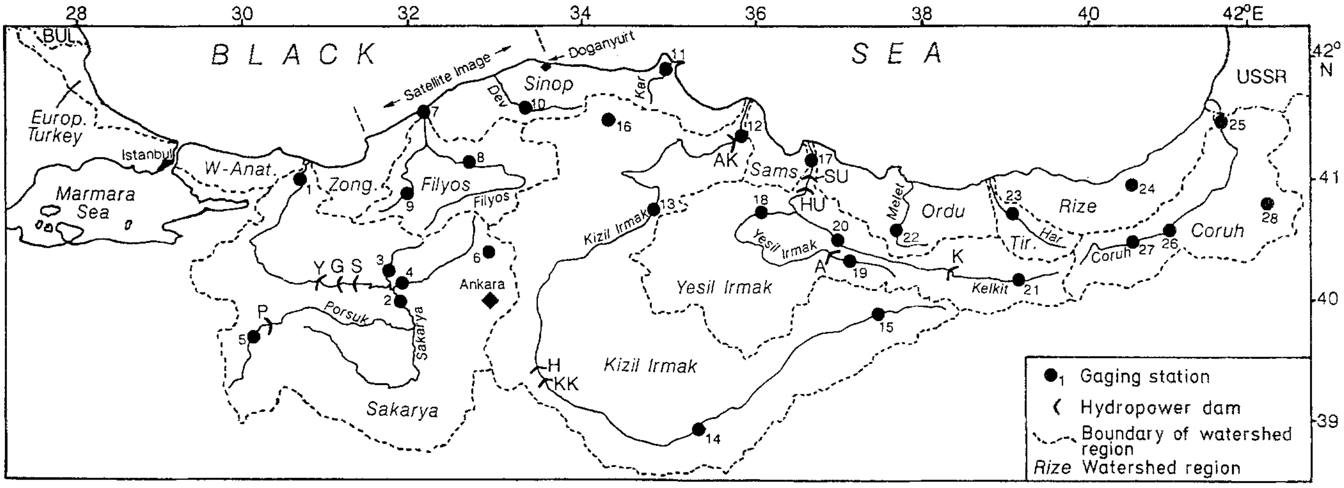

Fig. 1. Map of the watersheds of the five larger rivers: Sakarya, Filyos, Kizil Irmak, Yesil Irmak, and Coruh. The watersheds with numerous smaller coastal rivers were combined into regions (European Turkey, West Anatolia, Zonguldak, Sinop, Samsun, Ordu, Tirebolu, and Rize). Major dams and gaging station where data were collected by the EIE (1987) are marked. Hydropower dam abbreviations: Porsuk (P), Yenice (Y), Gökcekaya (G), Sariyar (S), Hirfanli (H), Kesikköprü (KK), Altinkaya (AK), Suat Ugurlu (SU), Hasan Ugurlu (HU), Almus (A), and Kilickaya (K). River abbreviations: Devrekani (*Dev*), Karasu (*Kar*), Harsit (*Har*). The arrows mark the coast line coverage of the satellite image in Fig. 6

Among the major rivers, the Sakarya river is located furthest to the west. It is the second longest river in Turkey (820 km), draining part of the Anatolian plateau in its upper reaches, before it breaks through the Pontic Mountains along the Black Sea. There are four large dams within the watershed (Fig. 1; Table 1). The Filyos river has the smallest watershed of the five major rivers and is confined to the Pontic Mountains in northwestern Turkey. There are currently no major dams along the Filyos river. The Kizil Irmak is the longest Turkish river (1360 km). It is the predominant river in the central parts of the Anatolian plateau, cutting across the Pontic Mountains northeast of Ankara. There are currently three large dams along the Kizil Irmak river. The watershed of the Yesil Irmak river consists of two major branches that converge about 80 km south of the mouth of the river: the Yesil Irmak branch in the west and the Kelkit tributary in the east. The Yesil Irmak branch drains part of the Anatolian plateau, while the Kelkit river is confined to the Pontic Mountains, following the course of the North Anatolian Fault. There are four major dams within the Yesil Irmak watershed. The Coruh river drains largely the region between the southern side of the high coastal Dogu Karadeniz Daglari to the north and the lower Mescit Daglari to the south. There are no major dams along the Coruh river at present.

Table 1. Major hydroelectric dams in northern Turkey[a]

River drainage basin	Major dams	Construction[b] Started (year)	Completed (year)	Surface area[b] (km^2)	Reservoir volume[b] (km^3)	Reservoir life-span[c] (yr) $W = 1.56$	$W = 1.29$
Sakarya	Yenice	under construction		3.64	0.058	54	45[b]
	Gökcekaya	1967	1972	20.00	0.91	540	450[b]
	Sariyar	1950	1956	83.83	1.90	1,100	920[b]
	Porsuk	1966	1972	23.40	0.43	4,400	3,700
Kizil Irmak	Altinkaya	1980	1988	118.31	5.76	520	430
	Kesikköprü	1959	1966	6.50	0.095	n/d	n/d
	Hirfanli	1953	1959	263.00	5.98	n/d	n/d
Yesil Irmak	Suat Ugurlu	1975	1981	9.70	0.18	23	19[d]
	Hasan Ugurlu	1971	1981	22.66	1.07	110	90[d]
	Almus	1958	1966	31.30	0.95	1,100	880
	Kilickaya	under construction		64.42	1.40	n/d	n/d

[a] n/d = No sediment transport data are available. W = Bulk density of sediments in the reservoir, measured in t/m^3

[b] Source: Government of Turkey

[c] This study

[d] The life expectancy of the three Sakarya river reservoirs in series (Sariyar, Gökcekaya, and Yenice Dam reservoirs) is cumulative, as the downstream reservoirs would not start to fill substantially until large quantities of sediment have settled in the upstream reservoir. This applies also to the two Yesil Irmak reservoirs in series (Hasan Ugurlu and Suat Ugurlu Dam reservoirs)

Methods

Data utilized in this study were obtained from a total of 28 gaging stations operated by the Electrical Resources Survey Administration in Turkey (EIE 1987) (Fig. 1). At each gaging station, EIE had typically measured water discharge rates and suspended sediment concentrations once a month. From the suspended sediment concentrations, EIE calculated sediment discharge rates. On average, EIE collected 143 measurements of both water discharge and suspended sediment at each gaging station. The systematic EIE sediment collection program was based on international standards of sediment transport characteristics.

Five of these 28 gaging stations were located close to the mouths of the major rivers Sakarya, Filyos, Kizil Irmak, Yesil Irmak, and Coruh (Fig. 1). Eight additional gaging stations were located upstream of hydropower dams along the rivers Sakarya, Kizil Irmak, and Yesil Irmak. Data from these additional stations provided estimates of the amount of sediment trapped by the dams. Four gaging stations were located along smaller rivers along the Black Sea coast; the Devrekani and Karasu rivers in the west and the Melet and Harsit rivers in the east. Data from these four rivers were used to estimate the discharge rates of the numerous ungaged smaller rivers. The remaining 11 gaging stations were located upstream throughout the Pontic Mountains and were studied for quality-control purposes. The available EIE (1987) data were utilized for the calculation of the weighted mean water and sediment discharge rates.

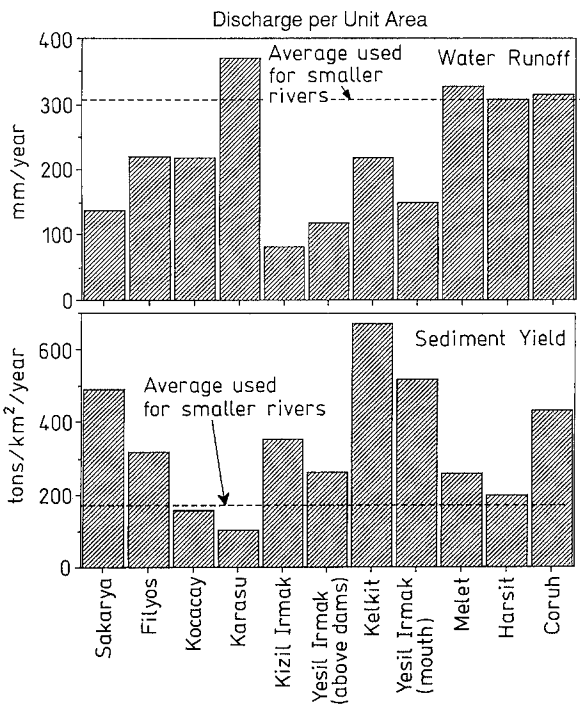

Fig. 2. Runoff and sediment yield of the five major Turkish rivers and four smaller coastal rivers. Shown also are the Kelkit river (gaging station 20 on Fig. 1) and the Yesil Irmak river above its confluence with the Kelkit river (gaging station 18 on Fig. 1). Water runoff calculations for the Sakarya, Kizil Irmak, and Yesil Irmak rivers are based on the entire watershed area. Sediment yield calculations for the Sakarya river are based on the area between the coast and the Yenice Dam. Sediment yield calculations for the Kizil Irmak river are based on the watershed area between the coast and the Hirfanli Dam using data from before the construction of the Altinkaya Dam. Sediment yield calculations for the Yesil Irmak river are based on the watershed area between the coast and the Almus Dam using data from before the construction of the Suat Ugurlu and Hasan Ugurlu Dams

The present-day water and sediment discharge rates at the mouth of the five largest rivers were calculated by adding the average annual discharge rates at the gaging station closest to the mouth of the respective river and a discharge estimate for the watershed area between these gaging stations and the river mouth. The pre-dam sediment discharge rates for the five major rivers were calculated by adding the present-day discharge rate at the mouth of the river and the sediment load measured above major dams for each respective river. All sediment discharge results were based on suspended sediment only; no bed load sediment data were available.

The present-day water and sediment discharge rates for the small coastal rivers were estimated from the discharge data of four small rivers from different areas along the Black Sea coast (Devrekani, Karasu, Melet and Harsit rivers; Fig. 1). These rivers are representative of the coastal rivers because they are very similar in their physiographic setting, watershed area, and vegetative cover. Extrapolation from these rivers to other rivers is reasonable since annual rainfall in the eastern and western Black Sea is similar. Mean annual rainfall from 1931 to 1974 was 680 mm in Istanbul in western Turkey, and 720 mm in Samsun near the mouth of the Yesil Irmak river along the eastern Black Sea coast (World Weather Disc 1989). Specifically, the discharge rates for the ungaged rivers were estimated as follows:

1. The coastal regions with ungaged rivers were divided into eight regions (Fig. 1). The area of each region was measured.
2. The average annual water and sediment discharge rates at the gaging stations along the Devrekani, Karasu, Melet, and Harsit rivers were determined in the same way as for the gaging stations along the five major rivers. The discharge rates at each gaging station along these four rivers were then divided by their respective watershed area to determine the unit area discharge rates per square kilometer for water and sediment, hereafter called runoff and sediment yield, respectively (Fig. 2).
3. The water and sediment discharge rates of the eight regions with ungaged rivers along the Black Sea coast were computed by using the mean of the runoff and sediment yield for the Devrekani, Karasu, Melet, and Harsit rivers.

The life-span of some of the major hydropower dams was estimated using the formula:

$$LS = [(W \times D_s)/Q_s] \times TE$$

where LS is the life span (yr), W is the mean bulk density of bottom sediments (t/m^3), D_s is the storage capacity (m^3), Q_s is the average suspended sediment load at a nearby gaging station (t/yr), and TE is the trapping efficiency (percent).

No data were available on the bulk density of the sediment in the Turkish reservoirs. Therefore, two different bulk densities (W) were used from life-span calculations for Lake Nasser at Aswan in Egypt; Shalash (1982) used W = 1.56 t/m^3 which may be a high value, and Smith (1990) used W = 1.29 t/m^3. The information about the storage capacity (D_s) of the reservoirs was supplied by the Office of the Chief Counselor for Economic and Commercial Affairs of the Embassy of Turkey in Washington. The average suspended sediment loads at nearby gaging stations (Q_s) was determined in this study; bed load sediment data were not available but are considered a comparatively small component of the total sediment supply. Estimates were made for the additional sediment supply between the gaging station and the four Sakarya river reservoirs and the Almus Dam reservoir. The trapping efficiency for the Turkish reservoirs was estimated after Stall (1980). The trapping efficiency (TE) determines the amount of sediment that is trapped by

Table 2. Discharges to the Black Sea by Turkish rivers[a] and other rivers[b]

Watershed	Size of watershed (km^2)	Water discharge presently (km^3/yr)	Detritus (10^6 t/yr) Presently	Detritus (10^6 t/yr) Pre-dams
Sakarya	46,400	6.42	6.19	8.84[f]
Filyos	13,200	2.91	4.18	4.18
Kizil Irmak	73,800	5.97[d]	0.46[e]	23.1[f]
Yesil Irmak	33,700	5.02	0.36	18.6[f]
Coruh[c]	19,900	6.18	8.13	8.13
Major rivers, sum	187,000	26.50	19.32	62.85
European Turkey region	1,700	0.52	0.31	0.31
West-Anatolia region	3,500	1.08	0.65	0.65
Zonguldak region	4,200	1.29	0.77	0.77
Sinop region	11,800	3.63	2.17	2.17
Samsun region	2,800	0.86	0.51	0.51
Ordu region	9,400	2.88	1.72	1.72
Tirebolu region	3,000	0.91	0.55	0.55
Rize region	9,800	2.96	1.77	1.77
Smaller watersheds, sum	46,200	14.13	8.45	8.45
Total (Turkish Rivers[c])	233,100	40.6	27.8	71.3
European and Asian rivers draining into the Black Sea[b]:				
Danube	836,000	198	83.00	
Dnestr	61,900	10	2.50	
Y. Bug	34,000	3	0.53	
Dnepr	538,000	52	2.12	
Don	446,000	28	6.40[i]	
Kuban	63,500	12.8	8.40[i]	
Caucasian Rivers	24,100	11.3[g]	6.79	
Rioni	15,800	4.9[h]	7.08	
Bulgarian Rivers	22,200	3	0.50	
Eurasian rivers, sum	2,041,500	323.0	117.3	
Total (all Black Sea rivers)	2,274,600	363.6	145.1	

[a] This study
[b] Shimkus and Trimonis (1974)
[c] Includes the Georgian part of the drainage basin of the Coruh, which comprises approximately 1480 km^2 or 7 percent of the total watershed of the Coruh
[d] River discharge before construction of the Altinkaya Dam minus an assumed 7 percent water loss which corresponds to the water loss in the Suat and Hasan Ugurlu Dams along the Yesil Irmak
[e] Assuming the same trapping efficiency of the Altinkaya Dam near the mouth of the Kizil Irmak as for the Hasan Ugurla and Suat Ugurla Dams along the Yesil Irmak of 98 percent of the sediment load
[f] Assuming all suspended sediment currently trapped by dams in the watershed reaches the Black Sea
[g] Estimated value based on the assumption that the Caucasian rivers have the same discharge per unit area as the coastal Turkish rivers
[h] Estimated value based on the assumption that the Rioni river has the same discharge per unit area as the adjacent Coruh river
[i] Most of the sediments from this river settles in the Sea of Azov

the reservoirs, which is a function of the volume of the reservoir relative to the inflow volume. These first-order life-span calculations (Table 1) assumed a linear relationship between sediment supply and reservoir filling; no allowance was made for the decrease in trapping efficiency towards the end of the life of the reservoir.

Results

The mean runoff of the four small coastal rivers was 307 mm/yr, which was generally higher than the runoff of the larger rivers that drain more arid regions of central Turkey, such as the Sakarya, Kizil Irmak, and Yesil Irmak rivers (Fig. 2 top). The runoff of the Filyos, Coruh, and the Kelkit rivers was similar to the mean runoff of the smaller rivers, probably because they are confined to the Pontic Mountains. The sediment yield of the four smaller rivers was 180 $t/km^2/yr$, which was lower than the yield for the larger rivers (Fig. 2 bottom). Highest sediment yields were measured for the Coruh, Sakarya, and Kelkit rivers.

Presently, the water discharge rates of the Kizil Irmak, Yesil Irmak, Sakarya, and Coruh rivers are above 5 km^3/yr each (Table 2). The water discharge rate of the Filyos river is about 3 km^3/yr. These five rivers account for about two thirds of the annual 41 km^3/yr of water supplied to the Black Sea by Turkish rivers. The remaining one third of the water is supplied by the small streams lining the mountain ranges along the coast.

Presently, the Turkish rivers supply approximately 28×10^6 t/yr of sediment to the Black Sea (Table 2). The highest sediment load is supplied by the Coruh river with

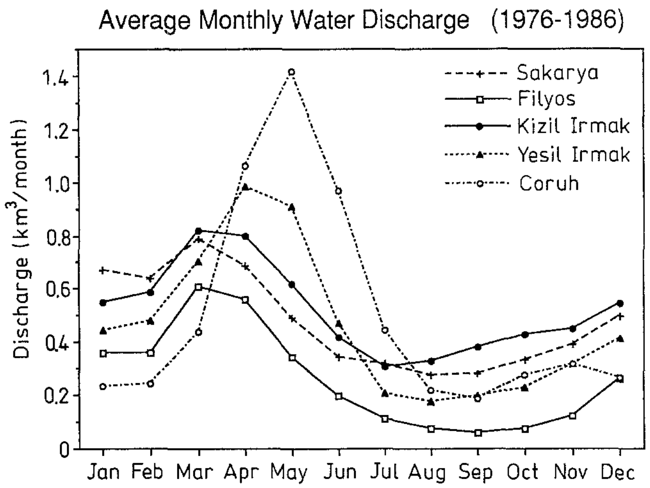

Fig. 3. Seasonal variability in water discharge rates of the Sakarya, Filyos, Kizil Irmak, Yesil Irmak, and Coruh rivers

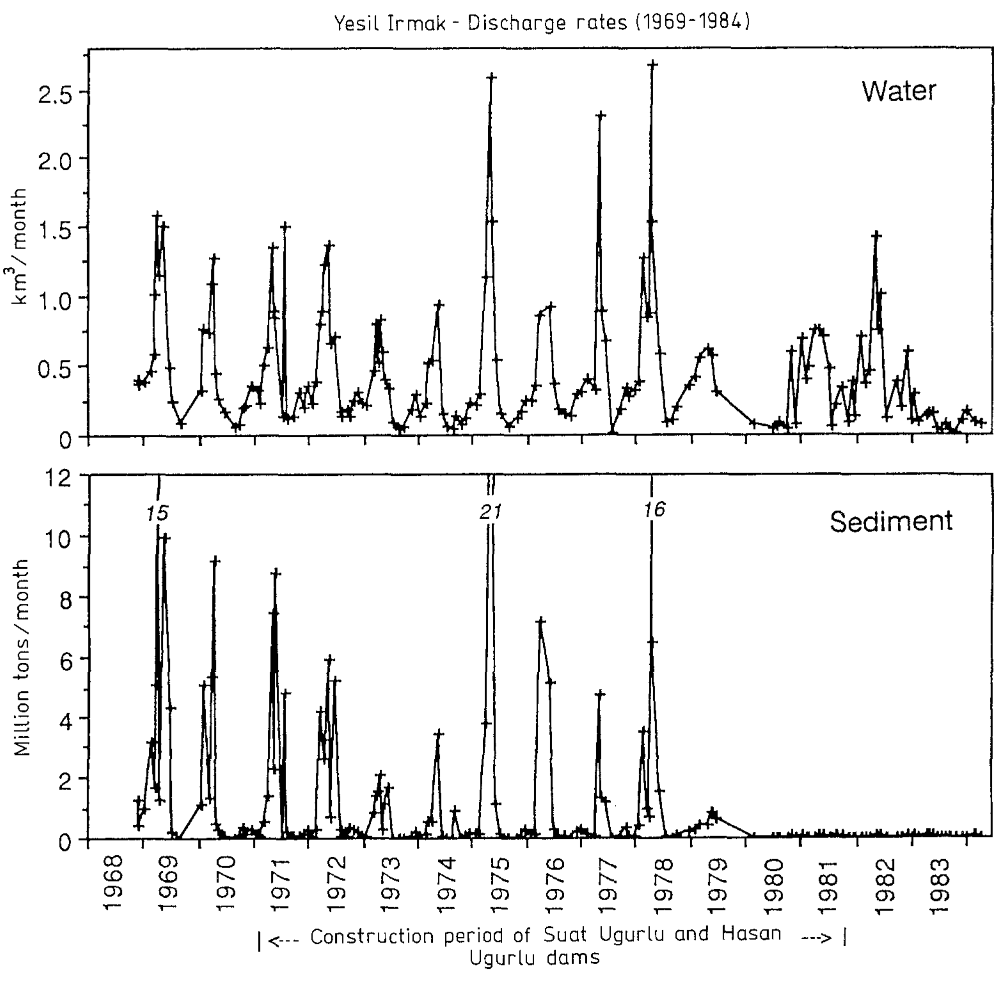

Fig. 4. Effect of the construction of the Suat Ugurlu and Hasan Ugurlu Dams near the mouth of the Yesil Irmak river on water and sediment discharge rates. The dams were completed in 1982, but the effect started to be noticeable in 1979. While the water discharge rate was reduced by the dams by only approximately 7 percent, suspended sediment is being captured by the dams by approximately 98 percent, leading to siltation over time

approximately 8 × 10^6 t/yr, followed by the Sakarya river with 6 × 10^6 t/yr, and the Filyos river with 4 × 10^6 t/yr (Table 2). The Kizil Irmak and Yesil Irmak rivers supply less than 0.5 × 10^6 t/yr each, because most of the sediment is trapped by the large dams near the mouth of the two rivers (Fig. 1). The Kelkit river carries about 30 percent more detrital matter than the Yesil Irmak river before they converge. About 30 percent of the total sediment discharged by Turkish rivers to the Black Sea is supplied by the ungaged smaller rivers.

Before construction of the hydropower dams, the sediment input of the Turkish rivers to the Black Sea was about 71 × 10^6 t/yr (Table 2). In other words, the construction of the dams reduced the sediment supply by 60 percent. About 88 percent of the sediment was supplied by the five largest rivers, compared to only 70 percent today. In the past, the largest amount of sediment was carried into the Black Sea by the Yesil Irmak and the Kizil Irmak rivers. The sediment discharge rate of the Yesil Irmak river was about 19 × 10^6 t/yr (Table 2). About 17 × 10^6 t/yr of the captured sediment is now trapped by the Suat Ugurlu and Hasan Ugurlu Dams; an additional 1.1 × 10^6 t/yr of sediment is trapped by the Almus Dam in the upper reaches of the Yesil Irmak river. The sediment discharge rate of the Kizil Irmak river in the past was about 23 × 10^6 t/yr. The sediment discharge rate decreased to about 18 × 10^6 t/yr after construction of the Hirfanli Dam in 1960. Presently, after construction of the Altinkaya Dam, the sediment of the Kizil Irmak river is nearly completely trapped. The sediment discharge rate of the Sakarya river before dam construction was 9 × 10^6 t/yr, about 40 percent higher than the current discharge rate (Table 2). About 2.5 × 10^6 t/yr of the sediment load of the Sakarya river and its tributaries Kirmir and Aladag are trapped by the Sariyar and Gökcekaya Dams. An additional 0.15 × 10^6 t/yr are trapped by the Porsuk Dam along the Porsuk tributary. Several other smaller dams with a reservoir surface area of less than 1000 km^2 exist in the upper reaches of the major rivers. The amount of sediment trapped by these reservoirs, however, is considered to be negligible for the total sediment load of the major rivers.

The season of peak discharge of all Turkish rivers is spring. The peak discharge month occurs later in the east than in the west, possibly due to longer winters and therefore later snow melting periods. Peak discharge occurs in March for the Sakarya river, in March and April for the Filyos and Kizil Irmak rivers, in April and May for the Yesil Irmak river, and in May for the Coruh river (Fig. 3). The sharp peak of the Coruh river is an indication of the snow melting effect. For rivers that drain parts of the Anatolian plateau, such as the Kizil Irmak, Sakarya, and Yesil Irmak, the monthly variability is lower. The monthly variability in sediment discharge rates corresponds closely to the variability in water discharge rates.

The damming of the Yesil Irmak river below the Suat and Hasan Ugurlu Dams resulted in a more uniform seasonal distribution of the water discharge rates due to flow regulation (Fig. 4). The average annual discharge rate was reduced by about 7 percent possibly due to evaporation

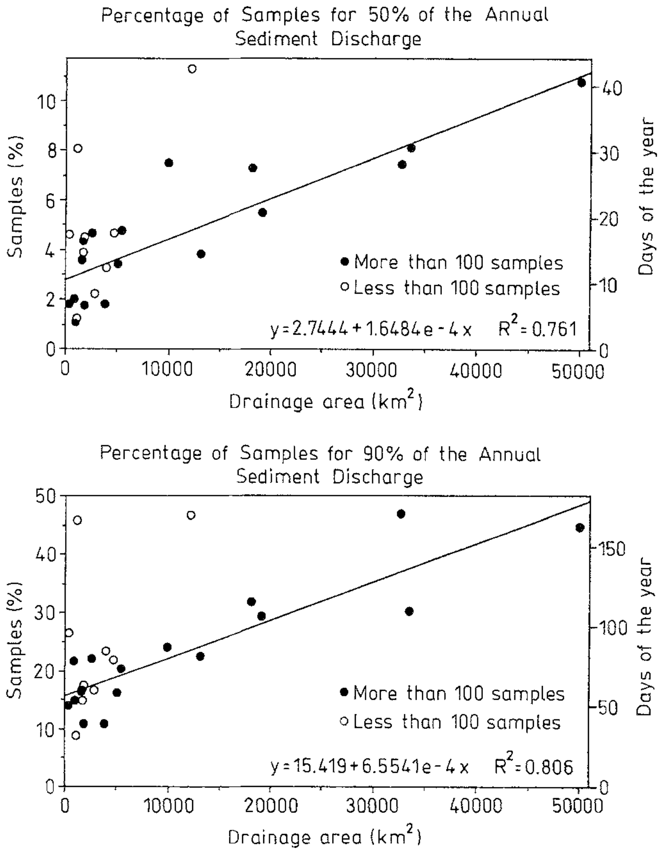

Fig. 5. Percent of all samples collected by the EIE (1987) over the last 20 years at each of the 28 gaging stations that carried 50 percent (top) and 90 percent (bottom) of the annual sediment discharge. Generally, most of the annual sediment load is discharged during fewer days with a decrease in the watershed area

and usage of water for irrigation. The sediment discharge rate was reduced by 98 percent.

Sediments in smaller streams is carried during much shorter time periods than in the larger rivers (Fig. 5). In the smaller rivers, 50 percent of the annual sediment discharge was measured by the EIE (1987) in less than 5 percent of all samples collected at each gaging station, which implies that 50 percent of the annual sediment is discharged by the rivers at the location of these gaging stations during less than 20 days out of the year (Fig. 5 top). This time period is about twice as long for the large watershed areas. Ninety percent of the annual sediment discharge was measured in about 15 percent of the samples collected, which implies that 90 percent of the annual sediment is discharged by the rivers at the location of these gaging stations during only about two months out of the year (Fig. 5 bottom). Again, this time period is about twice as long for large watershed areas. Therefore the statistical possibility of missing extreme discharge events during sampling is larger for smaller streams.

Reservoir life-spans for the major reservoirs vary considerably. The shortest life-span is estimated for the two Yesil Irmak reservoirs in series (Hasan Ugurlu and Suat Ugurlu Dam reservoirs). The combined life-span is estimated between 110 and 130 yr. Life-spans for the large

Altinkaya Dam reservoir on the Kizil Irmak is estimated between 430 and 520 yr. The combined life-span of the three Sakarya river reservoirs (Sariyar, Gökceckaya, and Yenice Dam reservoirs) is around 1500 years. The longest life-span was estimated for the Porsuk Dam reservoir with several thousand years.

Discussion

The water and sediment discharge rates of Turkish rivers to the Black Sea (Table 2) are higher than previous estimates. Bol'shakov (1970) estimated a water discharge rate of 25 km^3/yr and a sediment discharge rate of 17×10^6 t/yr. The sediment discharge rate for the Coruh river, however, is 47 percent lower than the 15.1×10^6 t/yr estimate of Mandych (1967).

The newly computed discharge rates seem reasonable based on denudation rates. Denudation rates are a measure of the average thickness of the soil layer eroded during runoff in the watershed. Denudation rates calculated from the data in this study are 0.23 mm/yr for all Turkish rivers and 0.33 mm/yr for the Coruh river. Degens and others (1980) computed denudation rates of Turkish rivers from data by Shimkus and Trimonis (1974) and estimates by Bol'shakov (1970) and Mandych (1967). While the rivers draining the Caucasus mountains, such as the Rioni, averaged between 0.19 and 0.30 mm/yr, the denudation rates for the Turkish rivers were calculated as 0.06 mm/yr and for the Coruh river as 0.61 mm/yr (Degens and others 1980). However, given the similarity in physiographic setting and climate, the denudation rate for the Turkish rivers (including the Coruh river) and the Caucasian rivers (including the Rioni) should have been similar.

The importance of the smaller coastal streams to the total sediment input to the Black Sea is supported by a LANDSAT satellite image from 27 April, 1984 (Fig. 6). The area on the image covers about 15 percent of the Turkish Black Sea coast (Fig. 1). The flow gaging data indicate comparatively high sediment loads during this time in April in the Filyos and the smaller coastal rivers. The sediment discharge of the Filyos river was 18 times the annual average on 19 April; the sediment discharge of the Karasu River was about three times the annual average on 25 April.

Compared to all rivers draining into the Black Sea, the water discharge contribution of Turkish rivers is comparatively small with 11 percent (Table 2). However, the present sediment load of Turkish rivers contributes about 19 percent to the total amount of sediment received by the Black Sea. Before dam construction, the Turkish rivers contributed over 35 percent of the sediment. The sediment contribution may have been even higher during historic periods of increased precipitation in Turkey. One such period was the Little Optimum between 1100 and 900 years BP, when climatic belts apparently shifted to the south, resulting in moister and colder conditions in the Near East (Lamb 1977; Erinc 1978). There are indications in the elemental composition of recent Black Sea sediments that during this time period sediments from Turkish rivers were a more predominant component in the eastern Black Sea (Hay and others 1991).

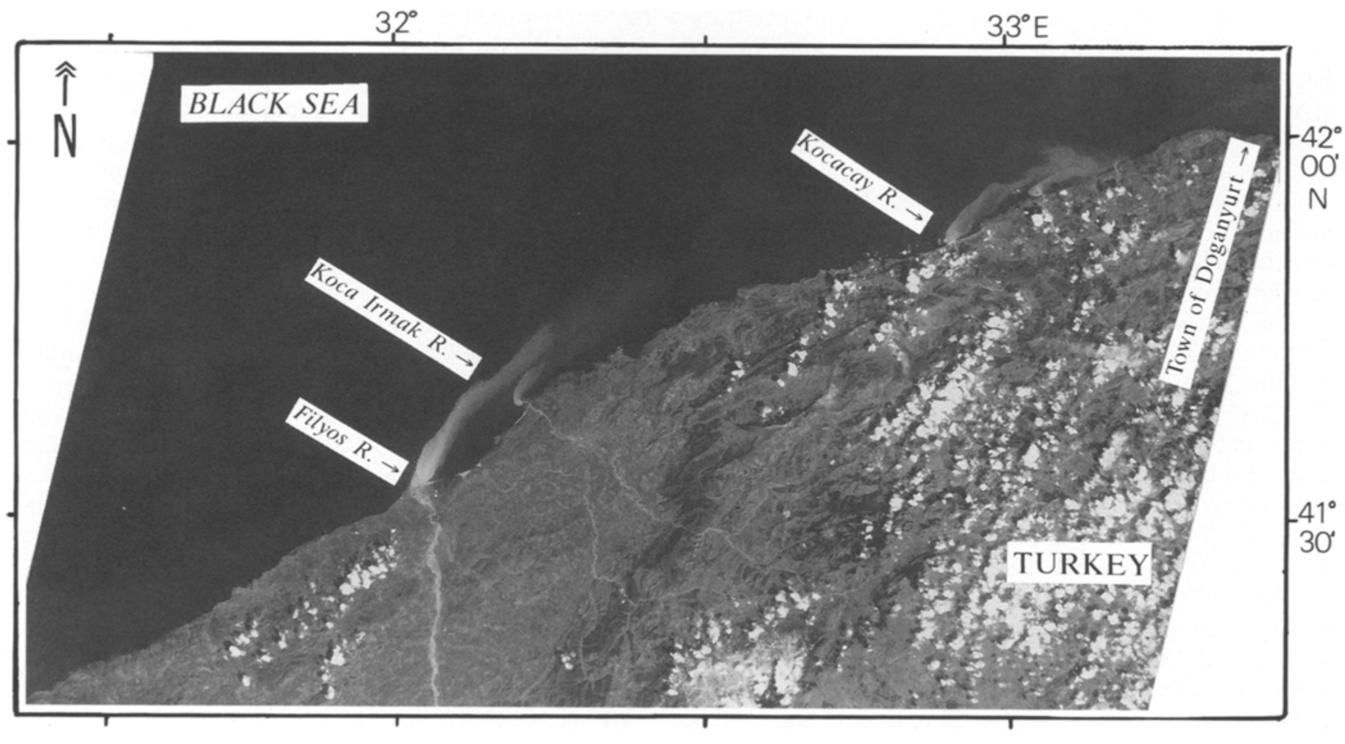

Fig. 6. LANDSAT image of the western Turkish Black Sea coast from 27 April, 1984. The most prominent plume on the image is from the Filyos River. The other plumes are from smaller coastal rivers

The life-span calculations for the larger reservoirs are best estimates based on available data. Refinement of these estimates would require selected field data collection of bulk density, trapping efficiency, and suspended sediment and bed-load sediment input from all sources into the reservoirs. Some of these data may already have been collected by Turkish or other researchers. Particularly desirable are refined life-span calculations of the two Yesil Irmak reservoirs (Hasan Ugurlu and Suat Ugurlu Dam reservoirs) with the short combined life-span of only around one century, which has important land management and electricity supply implications.

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