Riverine fluxes into the Black and Marmara Seas

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Abstract

The Black and Marmara Seas, two land-locked seas, constitute the eastern extension of the Mediterranean Basin. The Black Sea is a large depositional basin for the rivers discharging from extensive plains of southeastern Europe, the Caucasian Mountains and from northern Anatolia. Despite their smaller drainage areas and water flows compared to those of other rivers (Danube, Dnepr, Dnester), the Anatolian rivers produce a high sediment flux to the Black Sea because of the high relief of the Pontic mountains and the absence of any flood-plain. Anatolian rivers discharge 24 million t/y sediment and 40 km^3/y water into the Black Sea, based on 20-year data. Sediment fluxes of the Anatolian rivers display variations along south-west and south-east Black Sea, due to differences in relief and the amount of precipitation in the two regions. Fresh-water fluxes of the rivers in the eastern region are higher than in the western region. Most of the sediment is carried by rivers of the central and eastern sections of the Black Sea coast of Anatolia. The riverine fluxes into the Marmara Sea are less than 1 million ton/y suspended sediment and 5 km^3/y fresh water and derived mainly from the southern coasts.

Environmental setting

The Black Sea is the largest anoxic basin in the world; it is connected to the Mediterranean Sea via the Marmara Sea and its narrow straits, the Straits of Istanbul and Çanakkale (Figure 1).

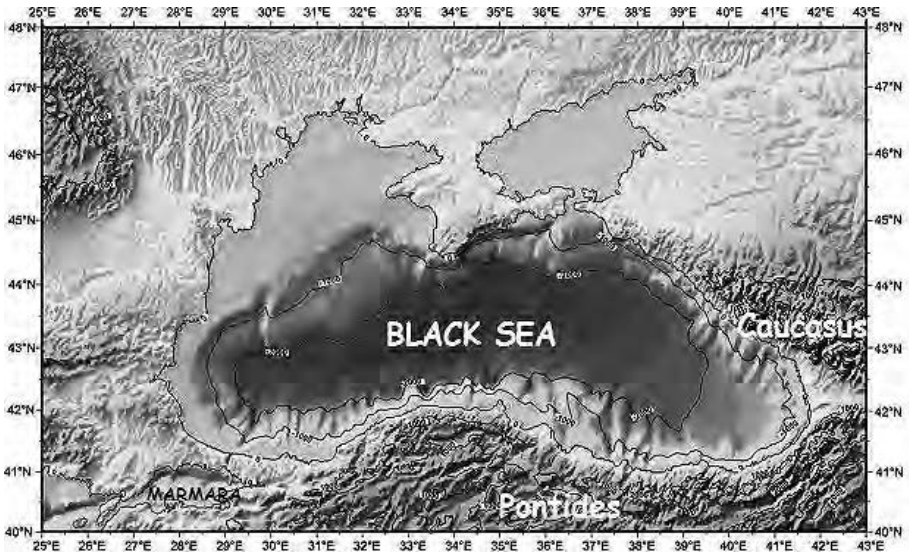

Fig. 1. Physiographic features of the Black and Marmara Seas.

Although the connection between these basins is restricted, their oceanography is closely related to each other. The fluvial sediments drained into the northern and northwestern part of the Black Sea are mostly trapped in the Danube Delta and Sea of Azov; however significant amount of suspended sediment and dissolved pollution loads from the Danube are transported towards the Istanbul Strait into the Marmara Sea by alongshore currents (Sur *et al*., 1994; Tuğrul and Polat, 1995).

The Black Sea has an approximate surface area of 425,000 km^2 which is one-fifth that of the Mediterranean Sea, and a volume of 537,000 km^3. It has a drainage area of about 2 million km^2 (1,864,000 km^2) which is almost five times greater than its surface area. Extensive plain in the west and north, and high-steep mountains in the south (Balkans and Pontides) and east (Caucasus) surround the Black Sea. 85 % of the drainage area belongs to flat relief, and only 15 % is part of the high mountains (Müller and Stoffers, 1974) where numerous small un-dammed rivers discharge into the Black Sea. The shelf area in the northwest is very wide due to accumulation of considerable amount of sediments carried by the rivers Danube, Dnester, Bug, and Dnepr (Figure 1).

The Marmara Sea is a small body of water with a surface area of 11,500 km^2 and a volume of 3,378 km^3. It is connected to the Mediterranean via Çanakkale Strait (62 km long and 1.2 -7 km wide) and to the Black Sea via Istanbul Strait (31 km long and 0.5-3.5 km wide). Less saline Black Sea waters (18-22 ppt) enter into the Marmara Sea, forming the upper layer, whereas the saltier and heavier waters of Mediterranean Sea (37.5-38.5 ppt) constitute the lower layer (Figure 2) (Ünlüata *et al*., 1990). Consequently, a permanent pycnocline between these two layers occurs at about 25 m water depth. The residence time of Black Sea originated upper layer is 4-5 months, whereas it is 6-7 years for the lower layer (Beşiktepe *et al*., 1994). Approximately 650 km^3/y of Black Sea water enters the Marmara Sea from the Istanbul Strait, but about 7 % of it is entrained into the lower layer. About 920 km^3/y of Mediterranean water enters from the Çanakkale Strait and 550 km^3/y of it enters into the Marmara Sea due to entrainment of 45 % into the upper layer in the Çanakkale Strait. 45 % of the amount reaching the Marmara is lost to the upper layer by basin-wide entrainment and 25 % of it entrains into the upper layer at the Istanbul Strait (Beşiktepe *et al*., 1994). As a result, only 300 km^3/y Mediterranean water inflows into the Black Sea. During this exchange, the Mediterranean water enters the Black Sea less salty (22 ppt) than when it started its passage at the Aegean end of the Çanakkale Strait (38 ppt) (Ünlüata *et al*., 1990). The Istanbul Strait annually carries 1.25 million ton/y of suspended solids from the Black Sea, whereas 0.9 million ton/y of suspended solids enters from the Çanakkale Strait (Baştürk *et al*., 1986).

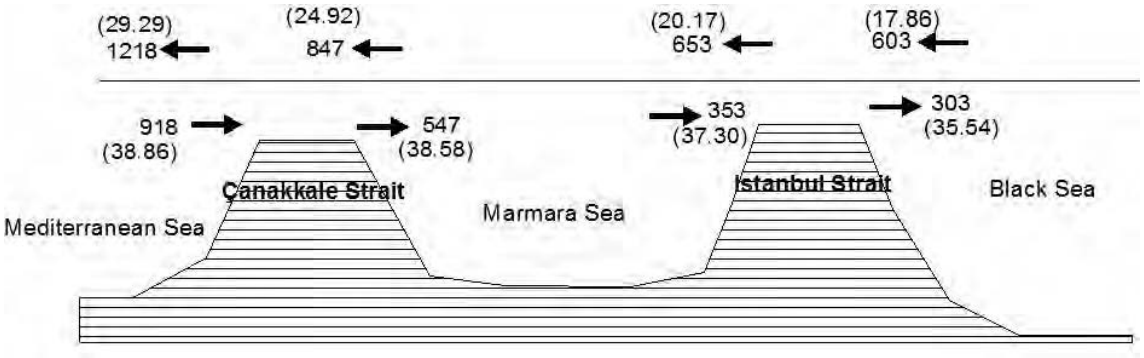

Fig. 2. Present-day water exchange between the Mediterranean and Black Seas across the Marmara Sea and TSS. Numbers in parenthesis indicate the salinity values (from Beşiktepe *et al*., 1994).

RIVERINE FLUXES INTO THE BLACK SEA: DISCHARGES FROM ANATOLIAN RIVERS

Total riverine water and sediment fluxes (after dam constructions) are summarized in Table 1. The Danube has the largest contribution with almost 50 % of the total water and sediment fluxes,

among the other rivers draining into the Black Sea. A substantial amount of the sediment carried by the northern and northwestern rivers flowing over the relatively flat Eastern Europe into the Black Sea is retained by the Danube Delta and the Sea of Azov. The annual contribution of small rivers (Georgian, Russian, Bulgarian and Anatolian), discharging from the mountainous areas are 54 km^3 water and 3 million ton sediment load (Table 1).

Table 1. Rivers discharging into the Black Sea: drainage area, water discharges and sediment loads (from Shimkus and Trimonis, 1974; Müller and Stoffers, 1974; Tolmazin, 1985; Ross, 1977; Algan *et al.*, 1999; Joashvili, 2003).

River	Drainage Area (km^2)	Water (km^3/yr)/ (% in total)	Sediment (10^6t/yr)/(% in total)
Danube	816,000	200	51.2
Dnester	75,200	9.1	1.73
South Bug	34,000	2.2	0.2
Dnepr	574,610	43.5	0.8
Don	422,000	28.0	7.75
Kuban	63,500	12.8	8.40
Bulgarian Rivers	8,678	1.2	0.8
Russian Rivers	5,079	6.3	1.6
Georgian Rivers	28,235	37	10.1
Anatolian Rivers	251,035	40	24
TOTAL		**380**	**107**
Only Small Rivers	10,749.6	54	3

Anatolian coasts of the Black Sea are mainly of erosional type with 20-30 m high cliffs, but depositional coasts with a relatively low topography (Kızılırmak and Yeşilırmak Deltas) are also locally present. Along the 1,625 km long (Darkot, 1975) Anatolian coastline, extending from Bulgarian to Georgian borders, five major rivers and various small rivers discharge their water and sediment load into the Black Sea. The majority of Anatolian Rivers are generally linear drainage patterns and short in length, compared to other rivers flowing into the Black Sea. Sakarya, Filyos, Kızılırmak, Yeşilırmak, and Çoruh are the major rivers, whilst Karasu, Devrekani, Harşit, İyidere, and Melet are the small rivers mainly located in the east part (Figure 3). The Kızılırmak is the longest river and has the largest drainage area (Table 2).

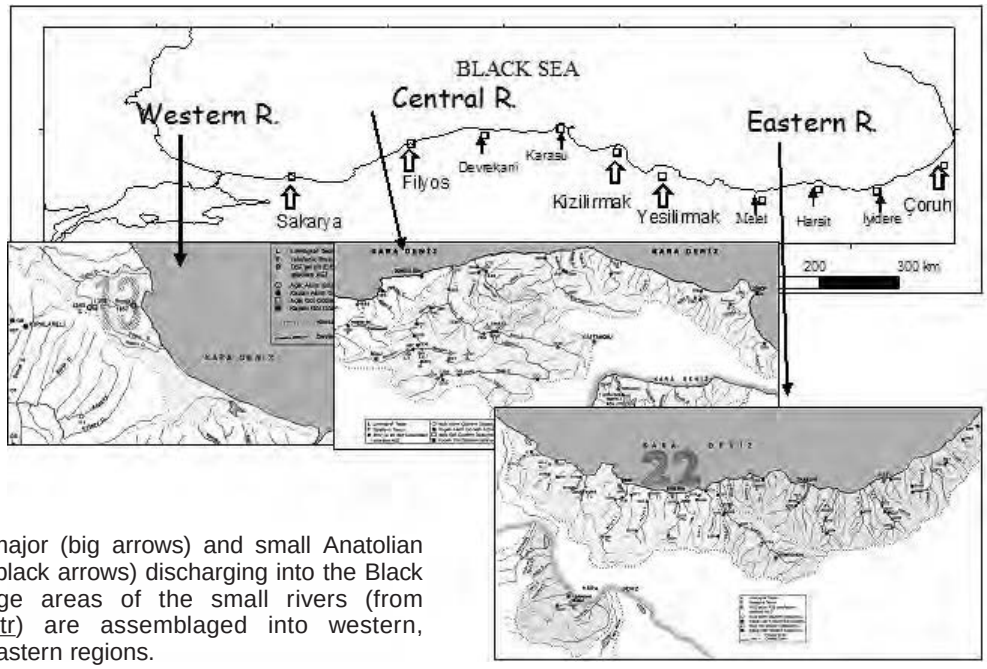

Fig. 3. The major (big arrows) and small Anatolian rivers (small black arrows) discharging into the Black Sea. Drainage areas of the small rivers (from www.eie.gov.tr) are assemblaged into western, central and eastern regions.

Average annual freshwater flux (20-year average between 1970 and 1990) of the Anatolian rivers is 40 km^3/y (Algan *et al*., 1999), contributing 10 % of the total water discharges into the Black Sea. The fresh-water discharge by rivers of the eastern and central regions is higher than by rivers of the western region because of the higher precipitation in the former regions. However, the high freshwater flux by the Sakarya River (14 %) is due to the large drainage area of this river (Table 2).

Table 2. Anatolian riverine fluxes into Black Sea: length, drainage area, water and sediment fluxes (Algan *et al.*, 1999). [1] Statistical Year Book of Turkey, 1985; [2] Atalay, 1994; zbırak, 1972; EIE, 1993; [3]Algan *et al.*, 1999; [4] calculated according to the same sediment load reduction rate of the Yeşilırmak; [5] Hay, 1994 and Aksu *et al.*, 2002.

Rivers	Length (km)[1]	Drainage A. (km^2)[2]	Water (km^3/yr)[3]	Sediment (10^6 t/y)[3]	Sediment (Pre-dam) (10^6 t/y)[3]
Sakarya	824	56,504	5.6	3.8 (1972-90)	4.6
Filyos	228	13,156	2.9	3.7	3.7
Small Western R.[5]		7,700	2.8	1.5	1.4
Small Central R.[5]		14,600	4.5	2.7	2.7
Kızılırmak	1355	78,646	5.9	0.4*	16.7
Yeşilırmak	519	36,129	5.3	0.33 (1979-84)	12.5
Small Eastern R[5].		22,200	6.8	4.0	4.0
Çoruh	466	19,984	6.3	7.5	7.5
Total		**248,919**	**39.7**	**23.9**	**53.7**

The suspended sediment load discharged into the Black Sea by Anatolian rivers is 24 million t/y (20-year average), contributing 22 % of the total load and derived mostly by the major rivers from the central and eastern regions (Algan *et al*., 1999). The highest sediment load is carried by the Çoruh River (7.5 million t/y; Figure 4). Kızılırmak and Yeşilırmak rivers appear to contribute only 2 % and 1 % of the total sediment load, respectively. However, prior to the completion of dam constructions in 1988 and 1981, Kızılırmak and Yeşilırmak rivers provided the Black Sea with more than half the sediments from Anatolia, amounting to 31 % and 24 % of the total at that time, respectively. The annual average sediment load of the Sakarya seems to have decreased since 1972 with the completion of Gökçekaya dam which is located close to the upper-course of Sakarya River.

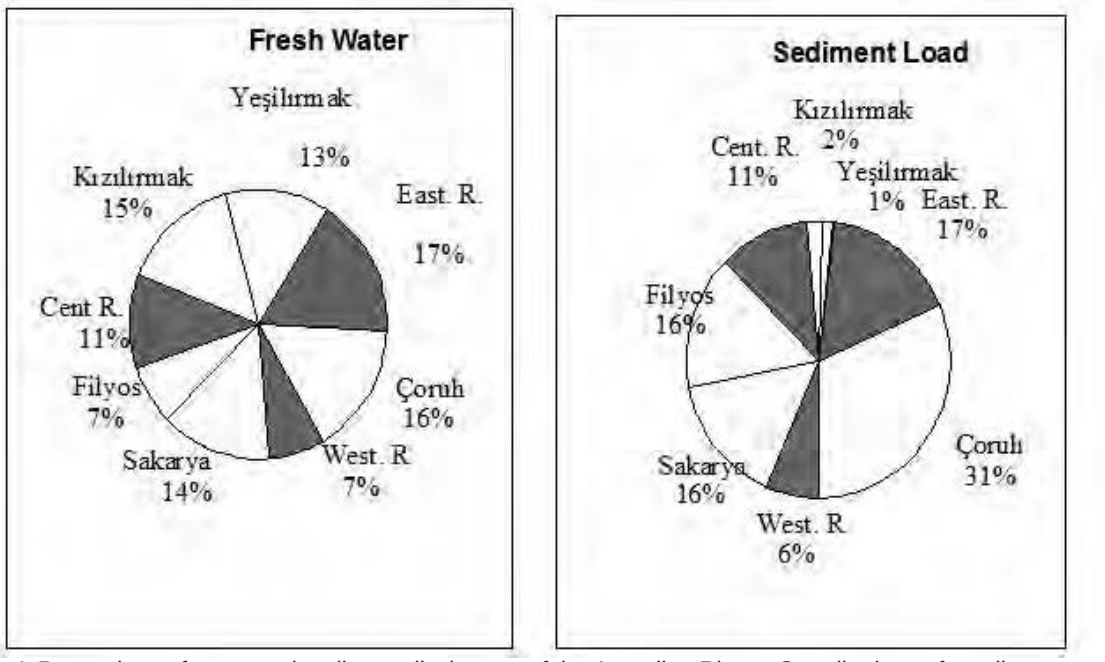

Fig. 4. Proportions of water and sediment discharges of the Anatolian Rivers. Contributions of small western, central and eastern rivers are shown in gray shades.

Maximum freshwater and suspended sediment fluxes of the major rivers (Çoruh, Yeşilırmak and Kızılırmak) generally occur in the spring, although this pattern shows small variations during the last 20 years (Figure 5). The sediment loads, with maximum discharges occurring in different months in the Sakarya and Filyos, start to increase in December and decrease in April, reaching their minima during summer. In the small rivers of the eastern region (Harşit, İyidere and Melet) the maximum discharges occurs between March and July, and the lowest in late summer (Figure6). All the rivers in the eastern and central region of the Anatolian Black Sea coast have similar characteristics, whereas the western rivers (the Sakarya and Filyos) seem to be influenced by climatic and topographical conditions different from those in the drainage areas of other rivers. The Sakarya River is longer and has a larger drainage area compared to those of the Yeşilırmak and Çoruh. The Eastern Black Sea region has a high relief with a maximum elevation of 3,932 m at Mt. Kaçkar, while the elevations and relief are much lower in the western region. The rivers of the northern slopes of the eastern mountains have much steeper gradients and narrower and deeper valleys than those of the southern slopes. Northern slopes of the eastern mountains receive higher precipitation than southern slopes. The eastern rivers receive the highest precipitation (rainfall and snowfall) between late autumn to late winter. An important portion accumulates in the mountains as snow and glaciers and melts during the spring, increasing river flow. The small rivers of the eastern region show peak sediment yields in spring and decrease in late summer. All the rivers in the eastern and central region of the Anatolian Black Sea coast have similar characteristics, whereas the Sakarya and Filyos rivers in the west seem to be influenced by climatic and topographical conditions different from those in the drainage areas of other rivers.

Two principal factors have strong impact on the sediment fluxes of Anatolian rivers discharging into the Black Sea: relief and precipitation. Despite their smaller drainage areas and water flows compared to those of other rivers (Danube, Dnepr, Dnester), the Anatolian rivers produce a high sediment flux to the Black Sea because of the high relief of the Pontic mountains and the absence of any flood-plain. The effect of relief can also be noticed among the Anatolian rivers. Most of the sediment comes from the eastern rivers (excluding the dam effects) with load being in the order: Kızılırmak>Yeşilırmak>Çoruh> Sakarya.

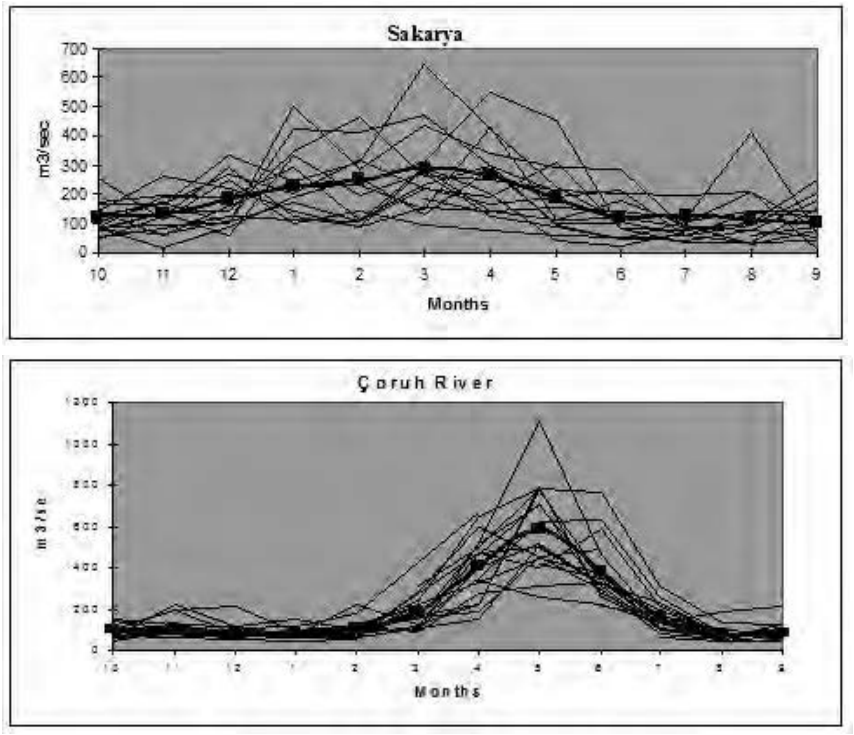

Fig. 5 a. Seasonal variations of water discharges from two major rivers (20-year data). Line with black squares denotes the 20-year average.

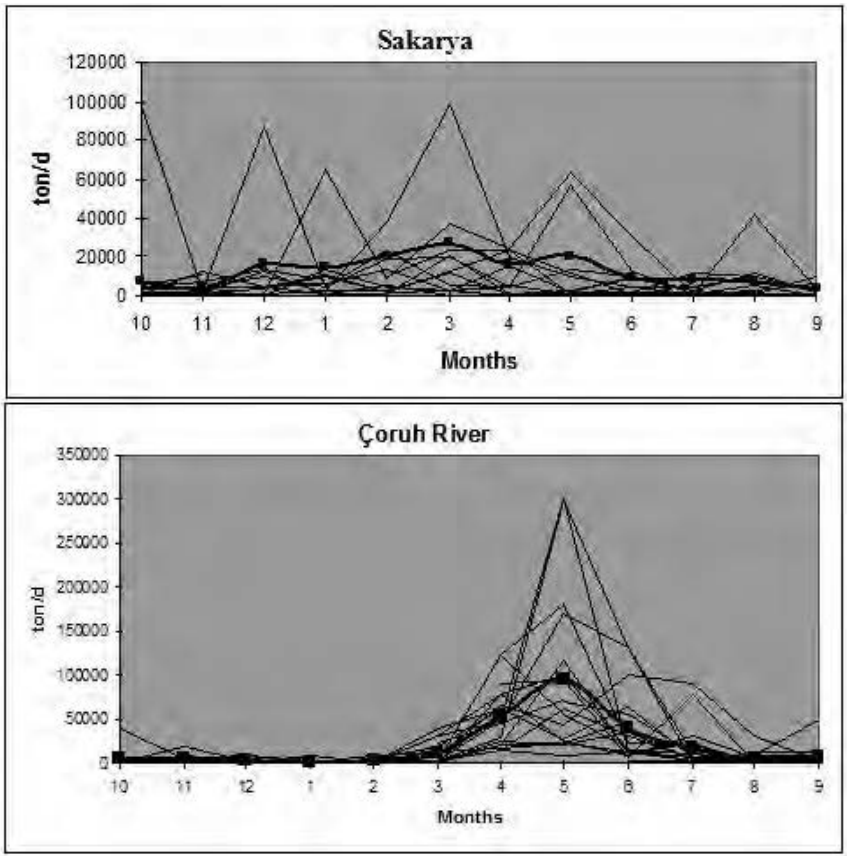

Fig. 5 b. Seasonal variations of sediment loads from two major rivers (20-year data). Line with black squares denotes the 20-year average.

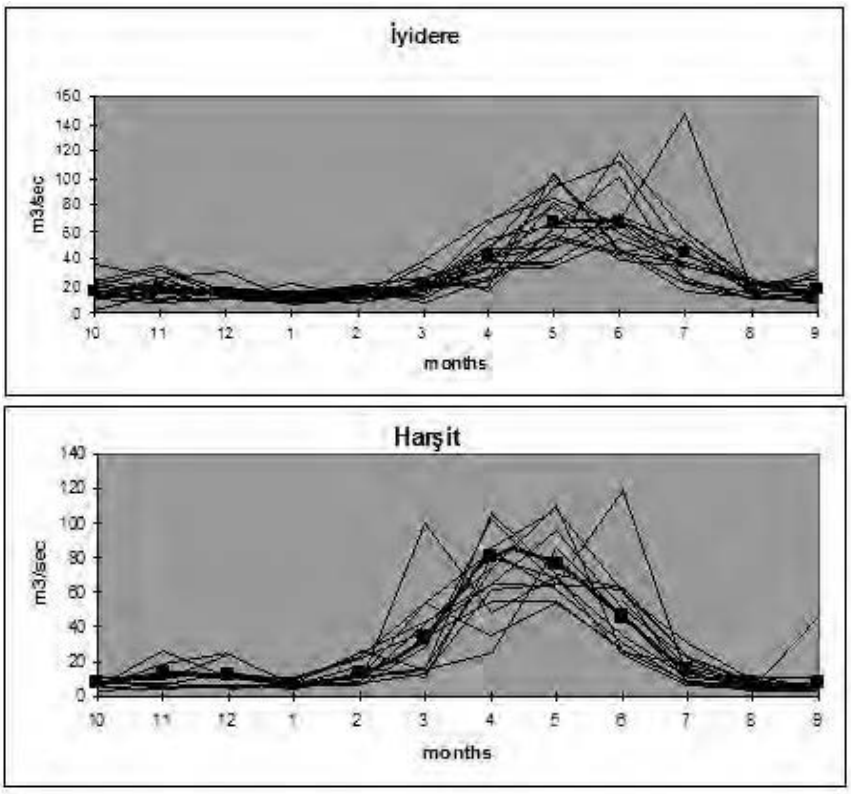

Fig. 6 a. Seasonal variations of water discharges from small eastern rivers (20-year data). Line with black squares denotes the 20-year average.

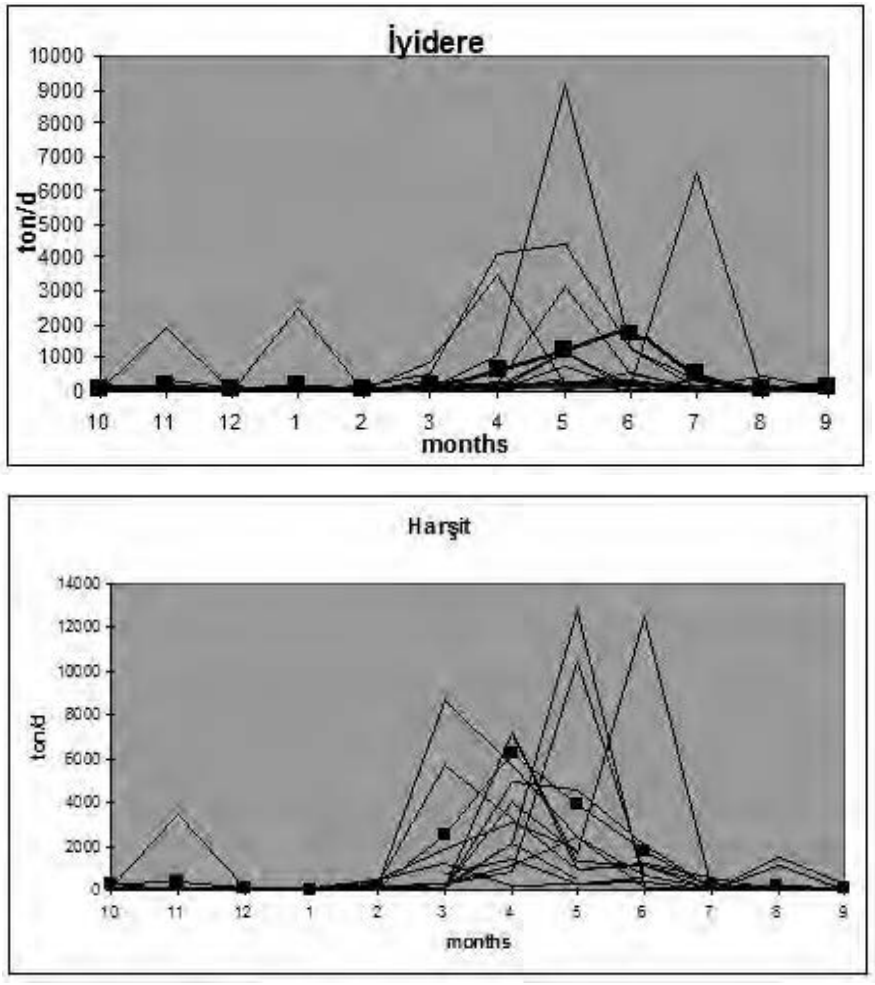

Fig. 6 b. Seasonal variations of sediment loads from small eastern rivers (20-year data). Line with black squares denotes the 20-year average.

RIVERINE FLUXES INTO THE MARMARA SEA

The Marmara Sea receives the major riverine influx from southern hinterland where relatively higher elevations are found, whereas the riverine input into the northern shelf which has a low topography, is negligible.

Table 3. Rivers discharging into Marmara Sea: drainage area, water discharges and sediment yields. [1] Statistical Year Book of Turkey, 1985; [2] Atalay, 1994; zbırak, 1972; [3] EIE, 1993.

Rivers	Length (km)[1]	Drainage A. (km^2)[2]	Water (km^3/yr)[3]	Sediment (10^6 t/y)[3]
Biga	108	2,096	0.6	0.1
Gönen	134	1,194	0.4	0.13
Kocasu/Susurluk	321	23,765	3.9	0.7
Total			**4.9**	**0.93**

There are mainly three rivers discharging into the Marmara Sea (Table 3) from the southern region. The riverine input from the northern region, where only linear small creeks are present is negligible. Kocasu/Susurluk River has the largest freshwater and suspended sediment fluxes. The total sediment load transported into the Marmara Sea is less than 1 million t/y (average between 1973-1990, EIE, 1993). The suspended sediment load of Kocasu River has reduced since 1982 after the completion of dam constructions. Maximum fresh water and suspended sediment fluxes of these rivers start in late winter and continue to spring.