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N. TH. SKOULIKIDIS

National Centre for Marine Research
Institute of Inland Waters
Agios Kosmas, Elliniko, 166 04 Athens, Greece

e-mail: nskoul@ncmr.gr

Abstract

The catchments of the interregional rivers (I.R.) entering Greece cover an area of approximately 98000 km^2, of which only 14% belongs to Greece, while their contribution to the country's freshwater runoff reach 40% (18 km^3/a). Geologically, the I.R. catchments are marked by their high percentage of acid silicates. I.R. show hydrochemical similarities, except for Evros, which is highly polluted. Compared to the other major Greek rivers, I.R. are the most polluted, with the Evros at the top, followed by the Axios. The main factors controlling their composition are climate, pollution and catchment geology. Inter-annual qualitative variations are controlled by seasonal climatic variations, which govern evaporation, groundwater contribution to river flow, dilution and flushing. A long-term salinisation of river water is attributed to climatic and anthropogenic impact. The I.R. transfer approx. 6,63 Mt dissolved solids to the sea annually. Regarding the inputs of pollutants into the sea, they transfer over 70 % of the potassium, nitrate and dissolved organic carbon of the total load carried by major Greek rivers (78% of total Greek surface runoff), whereas for phosphate and sulphate the percentages reach 89 and 78.

Keywords: Greek-interregional rivers, Typology, Hydrogeochemistry, Temporal hydrochemical variations, Pollution, Matter transfer.

Introduction

According to the Water Framework Directive (WFD-200/60/EC) integrated catchment management is a challenge for the near future. Managing Greek I.R. presents special difficulty. The existing number of international agreements is insufficient and, moreover, they are often violated. This happens because decisions are not based on the findings of shared management plans. These plans require knowledge of the relationship between the spatiotemporal water quantity and quality variations and the factors and processes responsible for them. One of the main components of integrated catchment management is the ecological quality characterisation of water bodies. This, in turn, is based on their typological characteristics. The aim of the article is to contribute to the implementation of the Water Framework Directive providing information on typological features, aquatic composition and pollution, temporal variations and controlling factors.

Materials and Methods

I.R. are characterised typologically according to the following features: catchment area, length, annual runoff, seasonal hydrological variations, catchment geology and hydrochemistry. Their hydrogeochemical character, stage of pollution and interpretation of intra-annual and inter-annual hydrochemical variations, are mainly based on previous research (SKOULIKIDIS, 1990, 1993, 1997, 1998, 2000), which is updated with recent data (MINISTRY OF AGRICULTURE, 2001).

Results and Discussion

Typology

The catchments of the I.R. entering Greece (the Evros, Nestos, Strymon, Axios) (Fig. 1), cover a total area of 97880 km^2, approx. 3/4 of the Greek territory. However, only 14 % of this area belongs to Greece. According to the WFD (System A) the catchments of Evros, Strymon and Axios are classified as very large (> 10.000 km^2), while the catchment of the Nestos as a large one (1.000-10.000 km^2). Figure 1 presents the I.R. and the other major Greek river catchments.

Greek surface runoff is approx. 45 km^3/year (KALLERGIS, 1979). This corresponds to 18% of Europe's runoff into the Mediterranean (250 km^3/year) (SKOULIKIDIS, 1997). 18 km^3/year or 40 % of the country's freshwater resources are supported by the I.R.

Regarding their natural annual hydrological regime (prior the construction of dams), the I.R. belong to the snow-rain type (MALIKOPOULOS, 1957), presenting two annual discharge peaks; one in winter due to

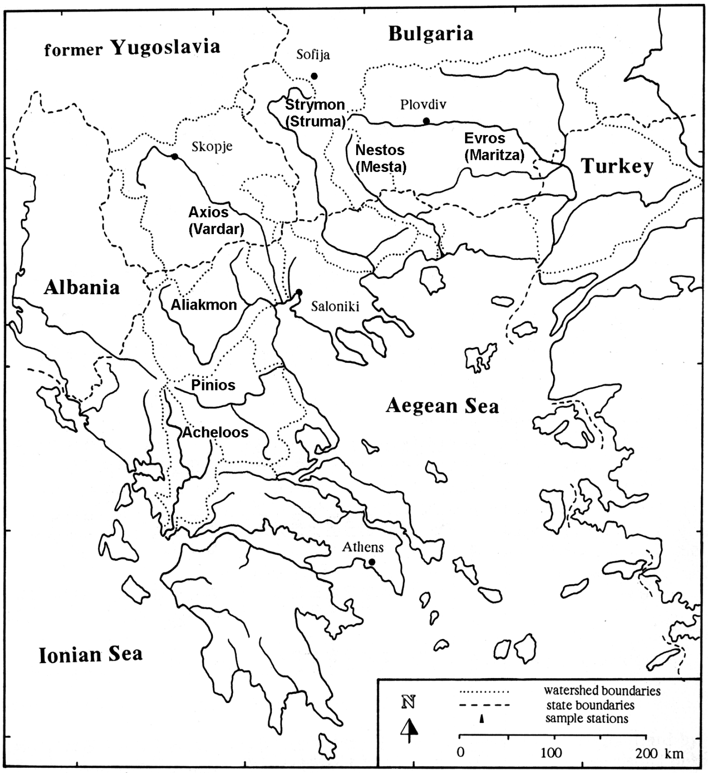

Fig. 1: The major Greek River catchments.

elevated rainfalls and the other in spring due to snow melting.

Geologically, the I.R. can be classified as silicate type rivers (WFD-System A), since they are characterised by high percentage of acid silicate rocks (38 - 68 %) and low percentage of carbonate rocks (10 – 17 %). In addition, the Evros, Strymon and Axios watersheds show a high percentage of neogene-quaternary sediments (32 - 42 %). The Nestos watershed presents some differences. It is marked by very high acid silicate percentage (68 %) and low percentage of neogene-quaternary sediments (18 %). Table 1 presents some typological characteristics of the I.R. and Figure 3 their geological and hydrochemical classification.

Hydrogeochemistry

In major Greek rivers (Fig. 1), riverine total dissolved solids (TDS) and total hardness (TH) are positively correlated to the percentage of neogene and quaternary sediments of their catchments (SKOULIKIDIS, 1993) (Fig. 2). This is mainly due to the high amount of calcite minerals in neogene and quaternary sediments (SKOULIKIDIS, 1990), which contribute to the total hardness of river waters. In addition, acid silicate rocks are characterised by low weathering rates (MEYBECK, 1981). The Evros, Strymon and Axios, with relatively high percentage of neogene and quaternary sediments in their catchments, are marked by a respective high TDS concentration (average 347 mg/l) in comparison to other Greek rivers. However, since carbonate rocks are weakly represented (average 13 %) and acid silicate rocks are strongly represented (average 41 %) their waters show low TH (average 3,51 meq/l $CaCO_3$), when compared with other Greek rivers. On the other hand, the Nestos, with its distinct catchment petrography, is marked by the lowest TH and one of the lowest TDS-value compared to other major Greek rivers. Since a part of the sodium in Greek rivers is attributed to waste water impact (SKOULIKIDIS, 1993) and mafic rock weathering strongly contributes to riverine silicate, potassium is the key ion for showing the influence of acid silicate rock weathering in I.R. In fact, in I.R. the contribution of the equivalent potassium concentration to TDS varies between 1,1 and 1,5 %, while in other major Greek rivers potassium represents only 0,5 - 0,6 % of TDS.

Multivariate techniques (Q-mode Cluster Analysis) show that, despite the different petrography of the Nestos (Fig. 3b), the Nestos, Strymon and Axios belong to the same hydrochemical group (Fig. 3a). The hydro-chemical similarity between the Nestos,

Table 1
Selected typological characteristics of Greek interregional rivers.

Rivers	Catchment (km^2) (% of Greek part)	Length (km)	Discharge (km^3/a)	Natural hydrological type	Geological type	Hydrochemical type
Evros	50425 (10)	530	6,8	snow-rain b[2]	acid silicate b[4]	Polluted[6]-hard[7]
Axios	24622 (7)	318	4,9	snow-rain b	acid silicate b	hard[7]
Strymon	16722 (36)	360	4,1	snow-rain b	acid silicate b	hard[7]
Nestos	6111 (40)	234	2,2[1]	snow-rain a[3]	acid silicate a[5]	Diluted[8]-medium hard[7]

1. Value calculated from the mean annual discharge (1,25 km^3/year) at Temenos station (4.393 km^2), (PUBLIC POWER CORPORATION, 1965-95) and the ratio between the discharge at the river mouth and the discharge at Temenos (1,73) (SKOULIKIDIS, 1990). **2.** Max discharge in spring, second peak in winter (MALIKOPOULOS, 1957). **3.** Max discharge in winter, second peak in spring (MALIKOPOULOS, 1957). **4.** High percentage of acid silicate rocks (usually > 35 %). **5.** Very high percentage of acid silicate rocks (> 50 %). **6.** SKOULIKIDIS (1993) **7.** Hardness classification after HEM (1970). **8.** Low conductivity (< 0,35 mS/cm).

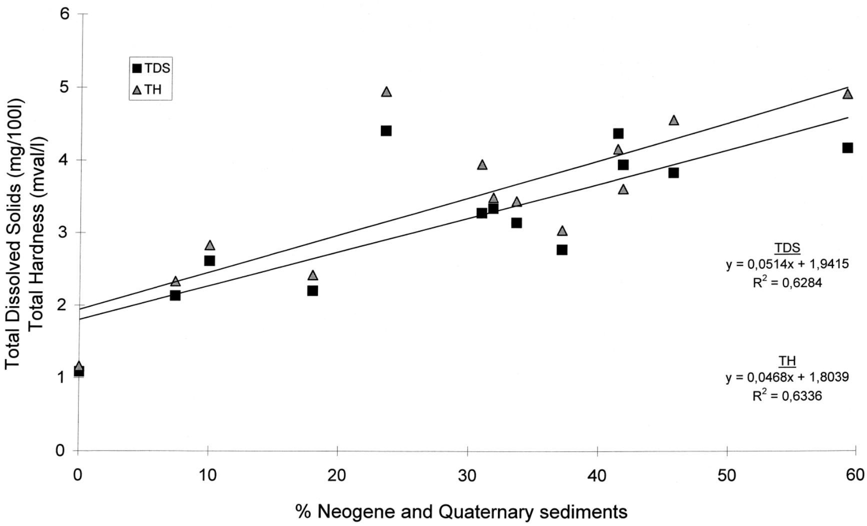

Fig. 2: Correlation between the percentage of neogene and quaternary sediments in major Greek catchments and the total dissolved solid (TDS) and total hardness (TH) concentration in the respective rivers (data: SKOYLIKIDIS, 1990).

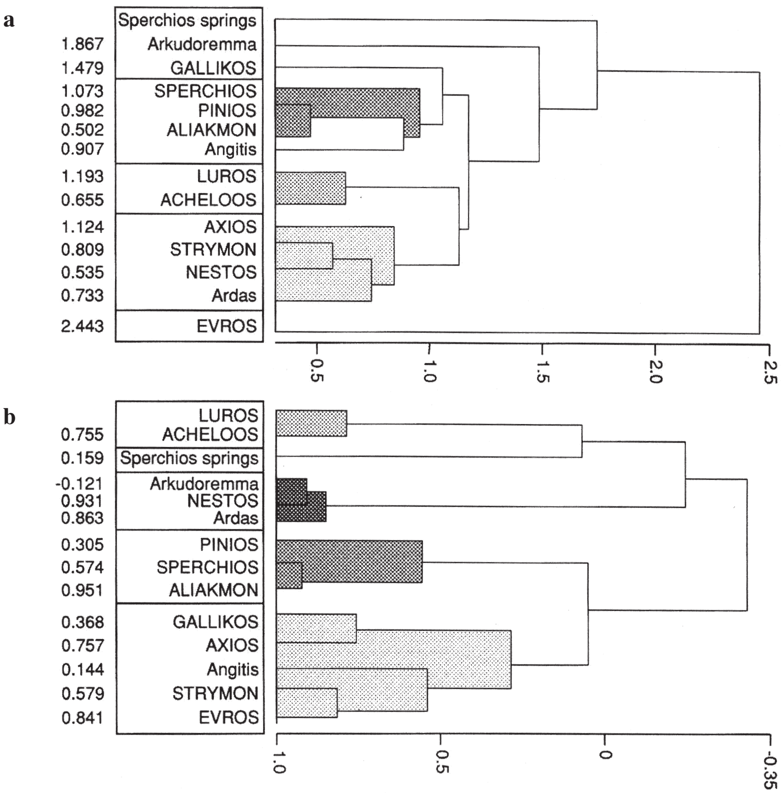

Fig. 3: Hydrochemical classification of major Greek rivers, **(a)**, geological classification of major Greek catchments **(b)** (SKOULIKIDIS, 1993).

Strymon and Axios is mainly attributed to catchment climatic features. In fact, Fig. 4 shows that different Greek hydrochemical river groups belong to respective climatic zones. The river that differs hydrochemically from the other I.R., despite their petrographic and climatic similarities (Fig. 3b, 4b), is the Evros. The hydrochemical differentiation of the Evros is attributed to its high pollution.

To conclude, catchment geology influences I.R. water composition. However, climatic features and pollution occasionally "mask" rock weathering.

Pollution

Evros shows more than double the sulphate and nitrate concentrations of the other I.R. (SKOULIKIDIS, 1993) and very high total phosphorous, nitrite and ammonia concentrations (MINISTRY OF AGRICULTURE, 2001) (Fig. 5). Therefore it is classified as polluted river (Table 1). According to their degree of pollution, all I.R. are located at the top of a list of 13 major Greek rivers (SKOULIKIDIS, 1993). The upstream countries are mostly responsible for this situation (SKOULIKIDIS, 1990). The Axios is

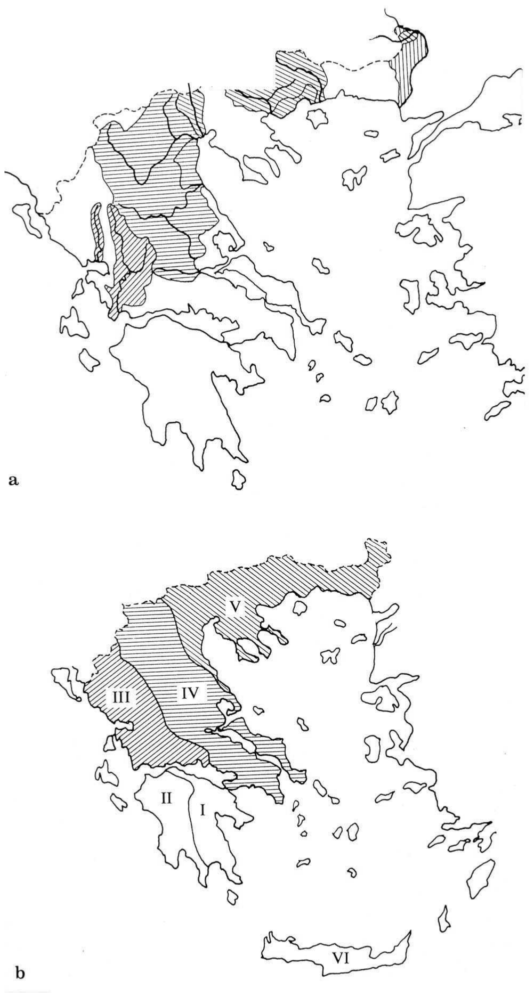

Fig. 4: Main hydrochemical Greek river groups, **(a)**, main climatic zones **(b)** (SKOULIKIDIS, 1993).

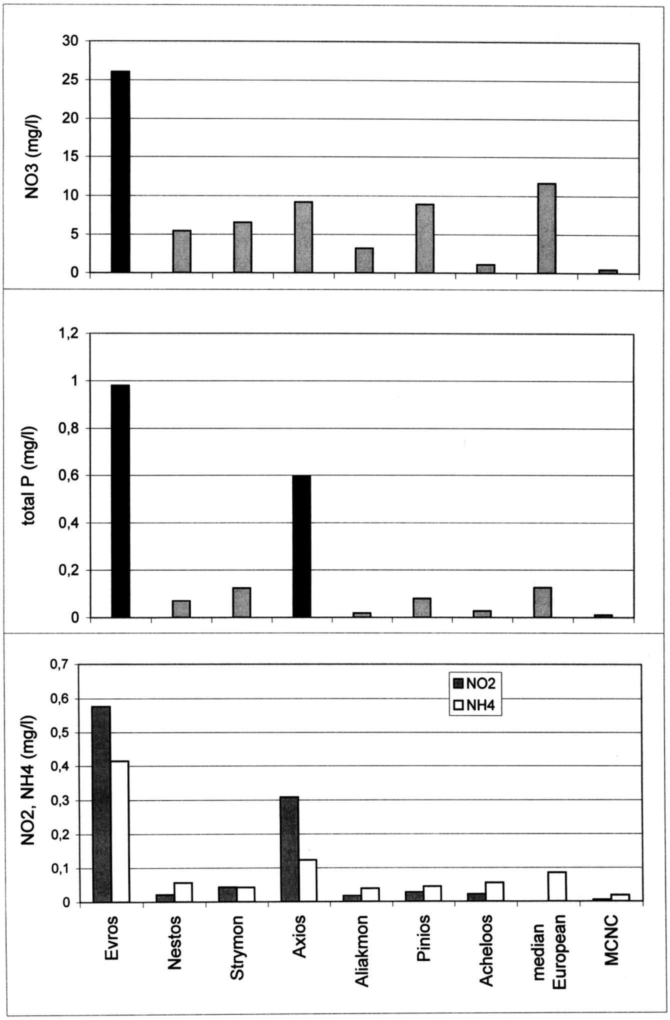

Fig. 5: Long-term (1980-97) average nutrient concentrations in major Greek rivers (data: MINISTRY OF AGRICULTURE, 2001). Median European levels according to STANNER & BOURDEAU (1995), MCNC: most common natural concentration (MEYBECK & HELMER, 1989).

the second most polluted Greek river with very high phosphorous, nitrite and ammonia levels (Fig. 5). As a result of its high catchment relief, the Nestos presents the lowest anthropogenic impact compared to the other I.R.

Intra-annual variations in river water quality

The seasonal regime of river water quality is controlled by three main processes, that are in turn governed by hydrological factors: (i) dilution, during springtime, when river discharge reaches its maximum, (ii) concentration, due to evaporation and the baseflow effect, during the dry season (in summer river water is practically represented by groundwater) and (iii) flushing of soil-salts, due to floods occurring in autumn/winter (e.g. Fig. 6).

Figure 7 presents the river discharge/ nutrient concentration relationship in the Axios. It is obvious that two different nutrient

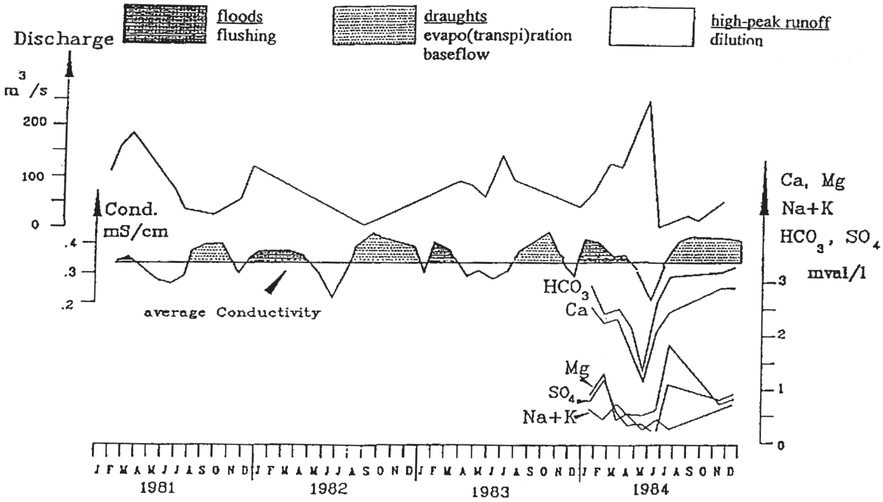

Fig. 6: Monthly variation of dissolved solids in Strymon R. at Rupel and its interpretation (SKOULIKIDIS, 1990 – data: MINISTRY OF AGRICULTURE).

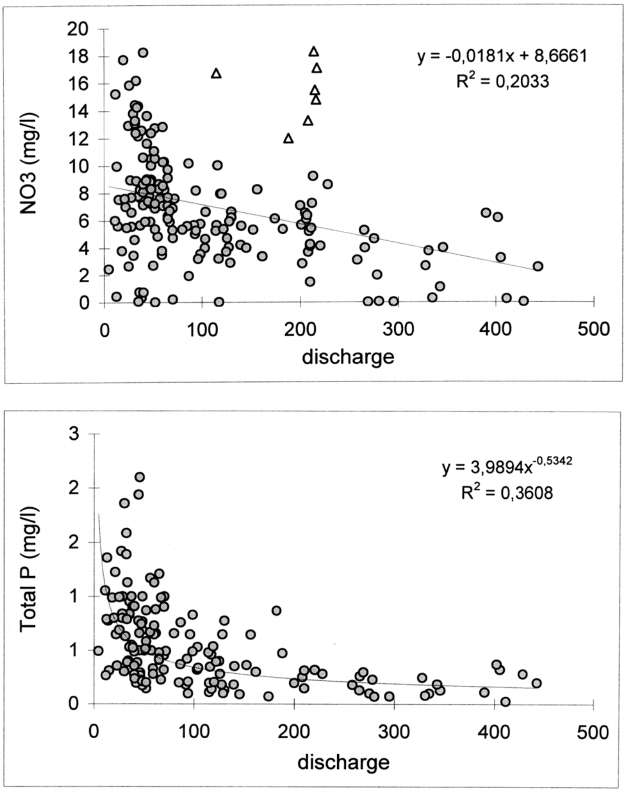

Fig. 7: Correlations between discharge and nutrients in Axios river at Evzoni (data: MINISTRY OF AGRICULTURE, 2001).

enrichment mechanisms are active: (i) impact of point sources of pollution, that are dominant during the dry season, resulting in negative discharge/ nutrient correlation and (ii) agricultural land flushing processes, that enrich river water with nitrates during autumn/ winter, occurring when discharge presents average values (Fig. 7 – white triangles).

Inter-annual variations in river water quality

All major Greek rivers show a long-term increase in their conductivity (SKOULIKIDIS, 2000). I.R. present the most dramatic inter-annual increase. Figure 8 shows the mean annual inter-annual conductivity trend for the Nestos, Strymon and Axios. Conductivity exhibits a mean annual increase of 4, 7 and 12 μS/cm respectively. In the Axios the overall conductivity increase reaches 40 %, within a period of about 15 years.

The long-term salinisation of Greek river waters is attributed to the following factors: (a) the droughts in the late eighties – early nineties (e.g. MIMIKOU, 1993), which influenced the evapotranspiration rates and diminished water resources. The latter caused a "concentration" of river water and an increase of baseflow proportion in river flow (baseflow effect), (b) the gradual reduction of river runoff, due to the expanding use of water resources for irrigation (baseflow effect), (c) the increase of irrigation activities as well as the increased use of sprinkler irrigation techniques in Greece (KOSMAS *et al.,* 1996), which cause salt accumulations in the upper soil profile and subsequent increased flushing processes and (d) the increase in river water pollution, which directly or indirectly (SKOULIKIDIS, 2000) enriches river water with dissolved solids.

Matter transport

According to SKOULIKIDIS (1990) I.R. transfer approx. 6,63 Mt dissolved solids to the sea annually, i.e. 55 % of the TDS carried by major Greek rivers (which cover 78 % of total Greek surface runoff). This is equal to their respective runoff contribution (56,5 %). However, regarding the inputs of pollutants, they transfer over 70 % potassium, nitrate and dissolved organic carbon of the total load carried by major Greek rivers. For phosphate,

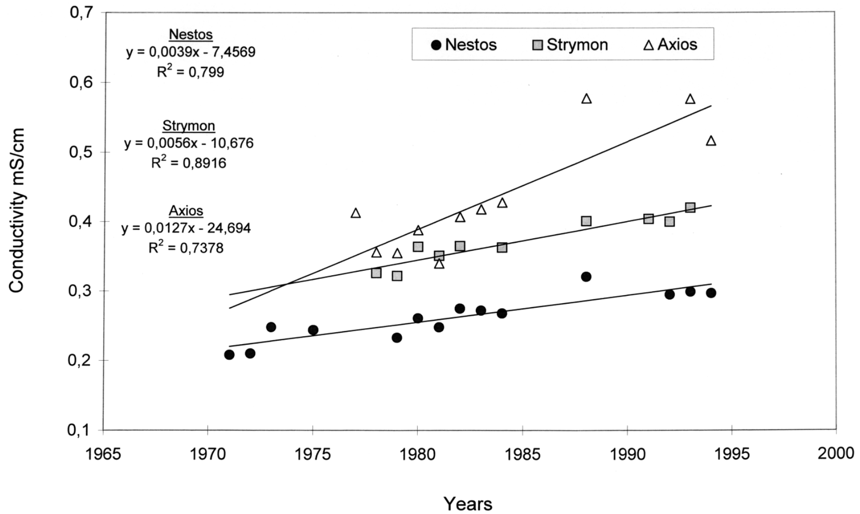

Fig. 8: Mean annual inter-annual conductivity trend in I.R. (data: MINISTRY OF AGRICULTURE, 2001).

the percentage is 89 %, and for sulphate 78 %. The Evros and Axios transfer 76 % of the phosphate and more than 50 % of sulphate, nitrate and suspended matter, while only the Axios (10 % of the major Greek runoff) carries 1/3 of phosphate. Finally, the Evros is responsible for more than the half of dissolved organic carbon input carried by major Greek rivers to the sea (Fig. 9).

Conclusions

Interregional catchments cover an area equal to 3/4 of the Greek territory, of which only 14% belongs to Greece, and contribute 40% to the total Greek surface runoff. Their catchments are classified as very large (Evros, Strymon, Axios) and large (Nestos). Geologically, they belong to the silicate type, with high amounts of acid silicate and neogene-quaternary rocks and low carbonate contribution. Catchment petrography causes relatively high TDS concentrations in the Evros, Nestos and Strymon, but low TH values, and very low TDS-TH levels in the Nestos. Other factors controlling water quality are climate and pollution. It seems that climatic factors "mask" the influence of geology (in the case of the Nestos), while pollution, "masks" geological and climatic factors (in the case of the Evros). Regarding pollution, the Evros is ranked at the top of 13 major Greek rivers, followed by the Axios, Strymon and Nestos. Within a hydrological cycle, dilution, evaporation/baseflow effect and flushing are the main processes that govern the seasonal

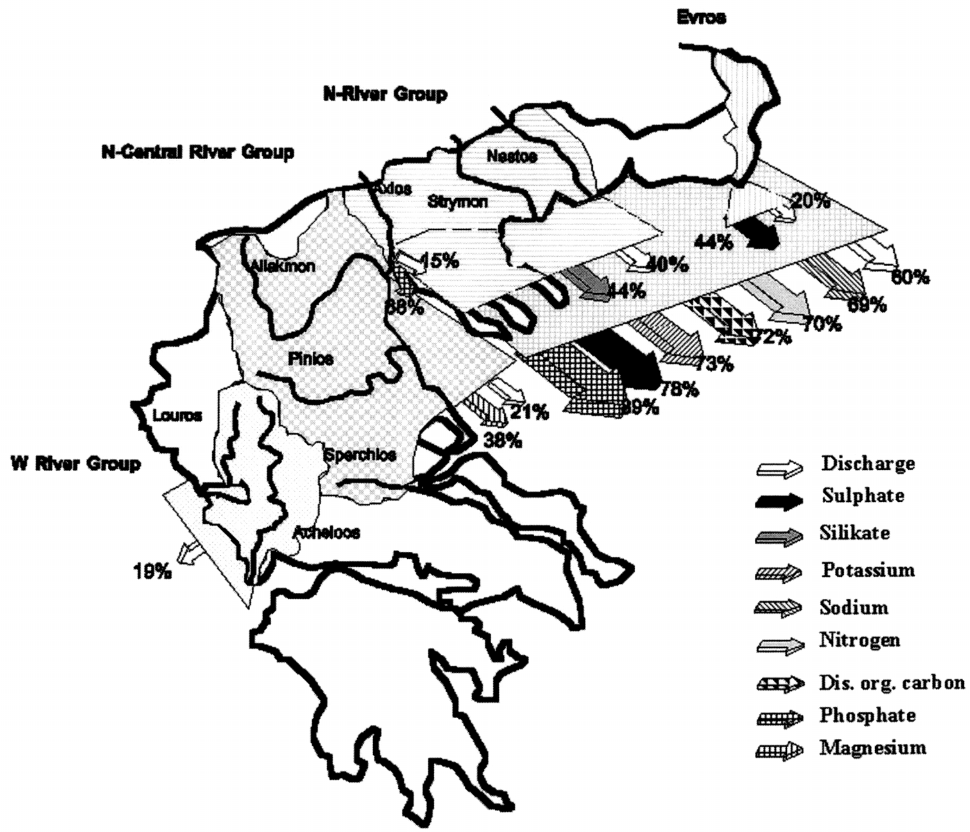

Fig. 9: Matter transport by major and interregional Greek rivers.

variation of dissolved solids. Compared to the other major Greek rivers, interregional rivers show the highest long-term enrichment in dissolved solid concentration. This gradual river water salinisation is attributed to droughts, abstraction of river water, increase in arable land, increase in sprinkler-irrigation and pollution impact. Interregional rivers transfer more than 70 % of nitrate, potassium and dissolved organic carbon to the sea, compared to the amounts carried by major Greek rivers (that cover over 3/4 of the total Greek river runoff). For phosphorous and sulphate the respective percentages are 89 and 78.

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