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INTERNATIONAL SPECIALIZED CONFERENCE
ON MARINE DISPOSAL SYSTEMS
İSTANBUL - TURKEY
9-11 November 1994

QUANTITATIVE COMPARISON OF THE INFLUXES OF NUTRIENTS AND ORGANIC CARBON INTO THE SEA OF MARMARA BOTH FROM ANTHROPOGENIC INPUTS AND FROM THE BLACK SEA

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ABSTRACT

The Sea of Marmara, an enclosed basin with two narrow and shallow straits permitting the exchanges of the Mediterranean and Black Sea waters, receives of 2.5×10^4 tons of total phosphorus, 2.8×10^5 tons of total nitrogen and 1.8×10^6 tons of total organic carbon per year totally from the Black Sea inflow, from the lower layer by vertical mixing and from anthropogenic inputs of various origins including riverine ones. The pollutant input from the Black Sea through the Bosphorus constitutes about 35, 60 and 75 % respectively of the total annual loads of TP, TN and TOC entering the Marmara surface waters. Pollution loads from Istanbul make up a major fraction (40-65%) of the total anthropogenic discharges. Biologically labile nutrients increasingly exported from the Black Sea in the early spring, are compensated by importation from the Marmara Sea through the Bosphorus underflow. The less labile input of dissolved organic nitrogen (DON) and organic carbon (DOC) (primarily terrestrial origin) from the Black Sea may reach the Aegean Sea in 4-5 months without contributing to the net production in the Marmara Sea. The present estimates indicate the biochemical properties of the Marmara upper layer (photic zone) to be mainly dominated by the nutrient inputs from the Black Sea and by mixing from the Marmara lower layer which is more pronounced in the Bosphorus-Marmara Junction (BMJ) region throughout the year. Waste inputs from the Istanbul Metrapolitan Area have the secondary importance for the nutrient and organic carbon pool of the Marmara Sea whereas the total inputs from other anthropogenic sources (riverine, industrial and domestic discharges) are dominantly effective at coastal areas and bays and this has resulted in dramatic local problems as in the bays of Izmit, Bandırma and Gemlik where water exchanges are limited.

KEYWORDS

Marmara Sea; Black Sea; Bosphorus; nutrients; organic carbon; anthropogenic sources; pollution.

INTRODUCTION

The Sea of Marmara, a semi-enclosed basin which has been subject to considerable human use and influence, connects the Black Sea to the Aegean Sea through narrow and shallow straits (Fig.1.). Therefore, the

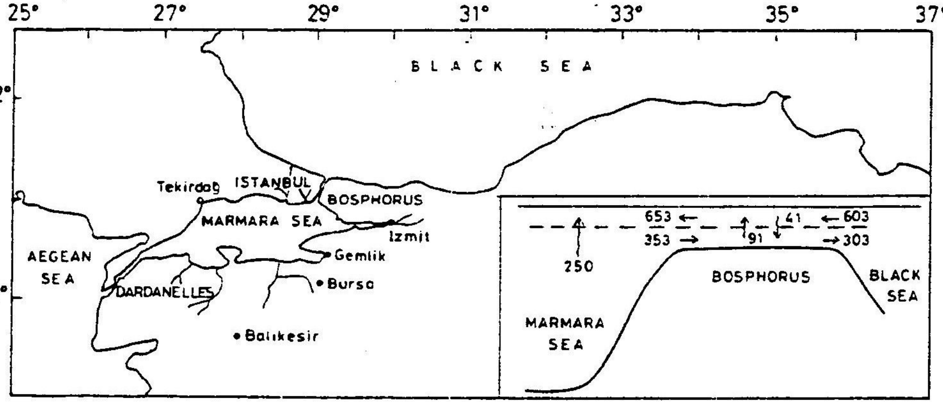


Fig.1. The study area (as a catchment basin) and the volume fluxes of water ($km^3\ y^{-1}$) in the Bosphorus region.

basin is occupied by two-distinctly different water masses throughout the year; brakish waters (22-26 ppt salinity) of Black Sea origin forming a relatively thin surface layer (10-15m) with a mean residence time of about 4-5 months, separated from the subhalocline waters of Mediterranean-origin (38.5-38.6 ppt salinity) by a sharp interface (pynocline) of about 10-20m thickness (Unluata et al., 1990; Besiktepe, 1991). Because of the large influx (about 600 km^3, see Fig.1.) into the relatively small upper layer volume (≈200 km^3), the Marmara Sea ecosystem has been influenced to a large extent by the inflow of biochemically modified surface water from the Black Sea. This Black Sea water has evolved from alongshore currents from the northwestern coastal margin which,in recent decades, have become polluted by river (mainly the Danube) and wastewater discharges (references cited in Mee, 1992). Unlike the inflow from the Black Sea, the Aegean salty waters entering the Marmara basin are relatively poor in both nutrients and organic carbon. However, during their stay of about 6-7 years in the basin, the inflowing, saline waters become enriched 10-fold with inorganic nutrients whilst their dissolved oxygen content drops from saturated to suboxic levels, 30-50 µM (Basturk et al, 1990), and consequently they leave the Marmara basin with markedly modified chemical properties.

The Marmara basin acts as a receiving water environment not only for pollutants from the adjacent seas but also for land-based chemical pollutants of various origins. According to the estimates of Orhon et al. (1994), the Istanbul Metropolitan Area (IMA), housing nearly 10% of the population in Turkey and about 40% of the industrial activity, is the major pollution source for the Sea of Marmara. Comparison of natural (Black Sea) and land-based inputs of nutrient and organic carbon into the Marmara Basin and of their export through the straits, should induce policy makers to develop a technically and financially sound masterplan for wastewater treatment and discharge so as to restore the changed ecosystem of the Marmara Sea. However, the implementation of such a management programme necesitates a through understanding of the principal hydrodynamical and biochemical properties of the Marmara Sea, including the two straits.

In this context, the systematic chemical data collected by the METU-IMS (Middle East Technical University - Institute of Marine Sciences) during

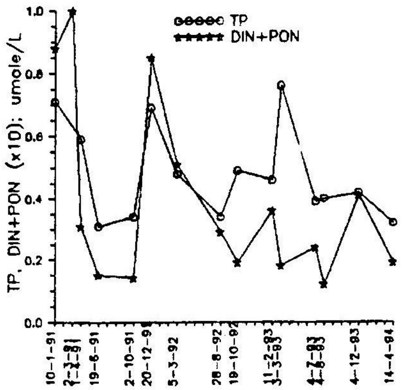
cruises of the R.V. Bilim in the Bosphorus Region between 1986 and 1992 have been examined extensively by Polat and Tugrul (in press) so as to estimate the exchanges of nutrients (nitrogen and phosphorus) and organic carbon between the Black and Marmara Seas. Orhon et al. (1994) have discussed various aspects of the pollution loads discharged from the IMA into the Bosphorus and the Marmara coastal margin and compared these with the exchanges of inorganic nutrients (disregarding the dissolved organic and particulate fractions) between the Black Sea and Marmara Sea. In this paper, we first summarise the inter-annual variability of the various forms of nutrients and the organic carbon in the Black Sea and Marmara waters exchanging through the Bosphorus, based on systematic data obtained during the 1986-1994 period, including more recent data than in Polat and Tugrul (in press). We then define the potentially important sources and sinks for the major chemical pools in the Marmara Sea, based on comparison of the annual estimates of chemical exchanges in the Bosphorus, the land-based pollution loads and the annual input from the lower layer to the surface water by vertical mixing.

CHEMICAL PROPERTIES OF THE OUTFLOW FROM THE BLACK SEA

The biologically labile nutrient and organic carbon contents of the Black Sea surface waters outflowing through the Bosphorus exhibit remarkable variations with season, as recently discussed by Polat and Tugrul (in press). Specifically, the nitrate (NO_3; actually nitrate+nitrite) concentrations, as high as 4.5-7.5 µM in winter, diminish to trace levels (<0.1-0.2 µM) in the summer-autumn period. Very high winter concentrations observed in both the Bosphorus (Polat and Tugrul, in press) and Romanian surface coastal waters (Bologa et al., 1981) imply that southerly along-shore surface flow, drastically polluted with nutrients of riverine and wastewater origin, may reach as far as the Bosphorus region without, under severe winter conditions, being consumed by photosynthesis. Dissolved inorganic phosphorus (IP; the so-called reactive phosphate) contents of the outflow exhibited a similar variation with season, ranging from <0.05 µM in the July-October period to values of 0.3-0.6 µM in winter. The estimated annual averages of IN and IP are 1.5 and 0.16 µM, respectively, in good agreement with the means given by Orhon et al. (1994) for the 1987-1989 period and by Polat and Tugrul (in press) for the 1987-1992 period. The annual average ammonia concentration, estimated as 0.5 µM for the outflow by Polat and Tugrul (in press), is about one-third the annual mean nitrate concentration, 1.5 µM.

Between 1991 and 1994 particulate organic nitrogen (PON) concentrations of the outflowing waters varied from 0.5 µM in summer to 5.5 µM during late winter - early spring, yielding an annual mean of nearly 2.0 µM. The particulate phosphorus (PP) data displayed a similar seasonality, remaining in the range of 0.07 to 0.23 µM with an annual average of 0.15 µM. The average concentrations of dissolved organic phosphorus (DOP) and dissolved organic nitrogen (DON, which is primarily of terrestrial origin and resistant to bacterial decay) have been estimated as 0.20 µM and 18 µM, respectively. The dissolved organic carbon (DOC) in the ouflow, primarily composed of less labile compounds, varied seasonally from 155 µM to 250 µM, yielding an annual average of 185 µM for the 1987-1994 period. More labile particulate organic carbon (POC), ranging from 7 µM to 40 µM with an annual mean of 17 µM , constitutes nearly 10% of the mean total organic carbon (TOC) concentration, 200 µM in the outflow. The POC:PON:PP ratios estimated from the annual means are nearly 112:13:1, consistent with the classical ratio of phytoplankton for the oceans.

The concentration of total phosphorus (TP), estimated from both the total of (IP+PP+DOP) and from direct measurements, ranged seasonally between 0.30 and 0.80 µM (Fig. 2a), with an annual mean of nearly 0.50 µM. Eventhough the TP in the outflow is composed primarily of IP in winter



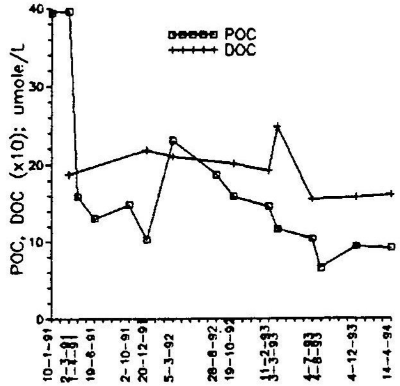


Fig.2. The time dependent variations of (a) labile nutrients: TP and IN+PON, (b) POC and DOC.

and PP during the bloom, the annual mean of TP comprises comparable levels of IP, PP and DOP. Biologically labile nitrogen (DIN+PON) constitutes about 20% of the mean TN (22.0 µM). However, at least 10% of DON in the ouflow may be assumed to decay on a weekly or monthly time scale since the large quantities of nutrients and organic materials in the waste and rivers discharged into the northwestern Black Sea shelf waters contribute labile DON to the coastal margin. As shown in Fig.2.a, the DIN+PON in the outflow increased to concentrations of 8.8-10.3 µM (mean: 6.7 µM) in the winter-early spring (December-March; however March 1993 value was not included because the concentration of both IN and PON were measured at unexpectedly low levels) but then decreased steadily to 1.2-3.0 µM (mean: 2.0 µM) during the late spring-late autumn period. Thus, even were the Black Sea outflow in the Bosphorus to be constant with time (in fact, it is not), the fluxes of biologically labile nitrogen (DIN+PON) and TP

TABLE 1. THE ANNUAL AVERAGE CONCENTRATIONS OF NUTRIENTS AND ORGANIC CARBON (µM) IN THE 1986-1994 PERIOD

Parameter	Brakish Outflow from the Black Sea	Saline Outflow from the Marmara Sea
Total Phosphorus (TP=IP+PP+DOP)*	0.51 (0.16+0.15+0.20)*	1.11 (1.01+0.05+ 0.05)*
Total Nitrogen (TN=IN+PON+DON) (IN=NH4+NO3)	22.0 (2.0+2.0+18.0) (0.5+1.5)	13.2 (9.8+0.4+3.0) (9.6+0.2)
Total Org. Carbon (TOC=DOC+POC)	202.0 (185.0+17.0)	72.7 (68.0+4.7)

* The numbers in parentheses represent the annual average concentrations of dissolved inorganic, particulate and dissolved organic forms of nutrients and organic carbon, respectively, which make up the total.

exported from the Black Sea during the winter - spring period probably exceed 2-3 fold the chemical fluxes during the summer-autumn period. The winter-spring and summer-autumn averages of POC concentrations were 22.7 µM and 13.0 µM respectively, giving an annual mean of 17 µM. On a total concentration basis, the annual variation of the TOC (possibly TN) concentrations in the outflow, is, however, of the order of 10% because these total values are primarily dominated by the biologically less labile DOC (and possibly DON).

NUTRIENT AND ORGANIC CARBON IN THE OUTFLOW FROM THE MARMARA SEA

In the Sea of Marmara, where photosynthesis is limited to the upper layer, including the interface between 15 and 30 m, nutrient and organic carbon concentrations of the subhalocline waters show much less seasonal variations than in the outflow from the Black Sea (Basturk et al., 1990). Between 1986-1994 nitrate and reactive phosphate concentrations ranged from 7 to 12 µM (annual mean: 9.8±1.36 µM) and from 0.7 to 1.3 µM (annual mean: 1.03±0.14 µM). The ammonia content of the outflow, as low as 0.2 µM, is certainly much less than the mean nitrate value, 9.8 µM. The outflow is also poor in particulate nutrients, varying between 0.17 and 0.60 µM for PON and between 0.04 and 0.07 µM for PP, with respective annual averages of 0.38 and 0.05 µM. The mean DOP, nearly 0.05 µM, is much less than the IP content of the outflow whilst the estimated DON value (3.0 µM) constitutes about 23% of TN (13.2 µM).

The DOC data from the subhalocline waters of the Bosphorus - Marmara junction exhibited small seasonal variations (Tugrul, 1993; Polat and Tugrul, 1994); the concentrations ranged between 58 and 76 µM with an annual average of 68 µM whilst the mean POC from the seasonal data (between 2.1 and 9.3 µM) was 4.7 µM, only 6% of TOC in the outflow (Table 1).

COMPARISON OF THE CHEMICAL INPUTS INTO THE MARMARA SURFACE LAYER FROM THE BLACK SEA, LAND-BASED SOURCES AND SUBHALOCLINE WATERS

The total nutrients and the organic carbon exchanged annually between the Black and Marmara Seas through the Bosphorus two-layer flows have been calculated from the average chemical concentrations and the recent volume fluxes, given in Table 1 and Figure 1 respectively, assuming these values to be constant on a yearly time scale. The chemical inputs from the subhalocline waters of the Marmara Sea mixed vertically into the surface layer, especially in the Bosphorus region and in winter throughout the basin, have been estimated from the vertical volume fluxes in Fig.1. and the average chemical concentrations of the upper sub-halocline (TOC= 75 µM; TN=12.0 µM; TP=1.0 µM). The pollution loads originating from Istanbul, 8.0×10^4 tons of TOC (estimated from the BOD_5/TOC=1.5 relationship given for municipal wastes by Benefield and Randall, 1980), 2.0×10^4 tons of TN and 3.3×10^3 tons of TP per year, were compiled from the data given in Orhon et al. (1994). The total waste inputs from the other sites of the Marmara region were taken from a project report prepared by Istanbul University in 1992 in which the annual loads of TOC, TN and TP have been estimated as 5×10^4, 1.7×10^4 and 1.5×10^3 tons respectively. The riverine inputs were derived from data from the State Water Authority (DSI, 1990) and the relationships given by Meybeck (1982) and the resultant annual loads are 5×10^4, 1.1×10^4 and 0.3×10^3 for TOC, TN and TP, respectively. The estimated annual inputs of chemicals entering the Marmara surface layer from the Black Sea, from land-based sources (including riverine discharges) and by the mixing of subhalocline waters are depicted in Figure 3.

The surface layer of the Marmara Sea receives about 2.5×10^4 tons of TP per year totally, with the largest contribution from the halocline waters

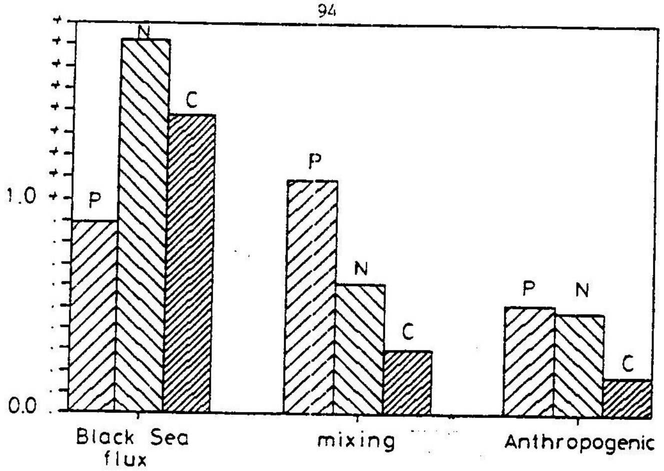


Fig.3. Annual comparison of TP ($x10^4$ tons), TN ($x10^5$ tons) and TOC ($x10^6$ tons) inputs by Black Sea inflow, vertical mixing and anthropogenic sources

($1.09x10^4$ ton y^{-1}). The TP input from the Black Sea ($0.89x10^4$), comparable with the input from the lower layer by mixing, is about twice the land-based input ($0.51x10^4$ ton y^{-1}), but 2.8 times the total input from Istanbul and 4.2 times that discharged into the Bosphorus Strait and BMJ region only. The TP imported from the Black Sea is nearly compensated by the export from the Marmara Sea through the Bosphorus underflow.

The TN import from the Black Sea ($1.7x10^5$ ton y^{-1}) is three times the export ($0.48x10^5$ ton y^{-1}) from the Marmara Sea to the Black Sea and more than 4 times the export to the basin surface by mixing and the pollution loads of land-based discharges. These comparisons have made disregarding the biodegradability of the DON which makes up a major fraction of the TN imported from the Black Sea. The import from the Black Sea is at least 9 times the total load originating from Istanbul. If only 10% of the DON in the Black Sea inflow is assumed to be utilized by biological processes in the Marmara Sea, the TN inputs from different sources are relatively unchanged; the Black Sea input is at least 2.5 times the total discharge from Istanbul and 4.5 times the pollution loads given to the Bosphorus and BMJ.

Similar ratios can be obtained when the TOC influxes into the Marmara surface waters are compared (Fig 3). The input from the Black Sea (about $1.4x10^6$ ton y^{-1}) is nearly 5-7 times the inputs mixed in from the lower layer ($0.3x10^6$ ton y^{-1}) and entering from land-based sources ($0.2x10^6$ ton y^{-1}).

A small fraction of the total TOC input (about $1.9x10^6$ ton y^{-1}) is composed of POC. A major fraction of the TOC carried by the Black Sea inflow into the Marmara Sea, which is much larger than the total load originating from Istanbul and elsewhere, is resistant to bacterial decay on a weekly or monthly time-scale. If only about 10% of the DOC in the Black Sea surface water is assumed to enter the biological loop of the Marmara Sea, the labile TOC input from the Black Sea ($0.24x10^6$ ton y^{-1}) becomes 3 times the TOC load from Istanbul, but 1.3 times the total anthropogenic inputs. Put simply, less labile organic matter entering the Marmara Sea from the Black Sea and other sources reaches the Aegean Sea through the Dardanelles on a time scale of a month without contributing to the net production in the Marmara surface water.

In this context, the chemicals exported from the Marmara lower layer by the Bosphorus underflow can be compared with the land-based pollution loads. The TP export from the Marmara Sea ($0.9x10^4$ ton y^{-1}) is nearly 3-times the total load from Istanbul; however it exceeds at least 4 times the TP discharged into the Bosphorus and the BMJ-region. A similar conclusion can be drawn for the TN which, in the Marmara outflow, is mainly composed of nitrate. The labile nutrients imported from the Black Sea is compensated by the exported load from the lower layer of the Marmara Sea in the form of ortho-phosphate and nitrate. However, one should note again that the DOC exported from the Marmara Sea is principally in a refractory form. Assuming only 10% of the DOC in the outflow to be labile on a monthly time-scale, the ratio of natural TOC exported from the Marmara to the total input from the IMA would be 0.45, increasing to 0.75 if only the TOC load to the Bosphorus and BJM-region is considered. Therefore, the deep outfalls of wastewaters from Istanbul, with their present TOC loads, are expected to cause to critical oxygen depletions in the Marmara lower layer waters (which are, indeed, currently poor in dissolved oxygen), especially in the regions of the discharges where the general circulation is relatively weak during the stratified seasons.

In the outflowing waters of the Marmara Sea the inorganic N:P ratio is about 10 which is less than the Redfield ratio. Thus, the nitrogen-rich waste discharged to the Marmara Sea ecosystem seems to facilitate the primary production in the surface layer. However, bio-assays performed in the western Izmit Bay indicated both phosphorus and nitrogen to limit the uptake of inorganic carbon by phytoplankton. This suggests further regional bio-assays and oceanographic studies are needed to define the environmental factors and processes controlling the algal growth with season. The annual inputs of nutrients and organic carbon from the Black Sea are at least 2-3 times the total pollution loads from anthropogenic sources. However, on a seasonal time-scale, for example, during the late summer-autumn period when both the water flow and the concentrations of non-conservative chemicals decrease in the Black Sea outflow, the anthropogenic input may be as large as the natural inputs from the Black Sea.

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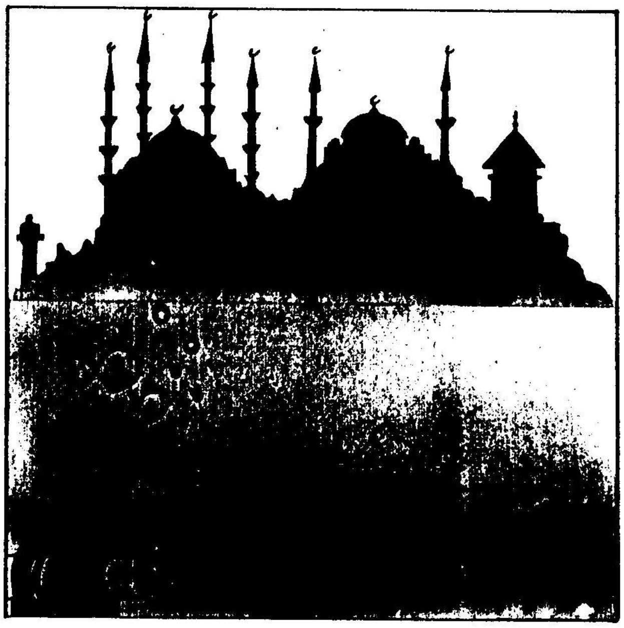

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