MONITORING VIA DIRECT MEASUREMENTS OF THE MODES OF MIXING AND TRANSPORT OF WASTEWATER DISCHARGES INTO THE BOSPHORUS UNDERFLOW

FINAL REPORT
VOLUME 1 / TEXT

HYDROGRAPHY, SEA-LEVEL, CURRENT AND FLUX MEASUREMENTS IN THE BOSPHORUS STRAIT, AND ACOUSTICAL, CHEMICAL AND RHODAMINE-B DYE TRACER STUDIES OF THE AHIRKAPI WASTE DISCHARGE

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CHAPTER 1

INTRODUCTION

1.1 The Purpose and Objectives of the Study

The purpose of the project was to monitor the wastewater discharge system of the City of İstanbul, and evaluate its performance with respect to the environment through direct measurements of the wastewater effects in the Bosphorus and the adjoining regions. The project objectives included testing (via direct measurements) of the earlier hypotheses (based on long-term measurements and budgets) on the dilution of wastes in the marine environment and the mixing between the lower and upper layers of the Bosphorus.

During the studies, regular observations, including hydrographic, chemical and current measurements, were made within a station network shown in Figures 1.1 and 1.2. Rhodamine-B dye tracer experiments were performed several times to study the effects of wastewater discharges in the Bosphorus Strait and in the adjacent waters.

1.2 Earlier Studies and Other Relevant Literature

A number of earlier studies were carried out by the IMS-METU to determine the environmental variables influencing the City of İstanbul wastewater discharge system, and to provide a basic understanding of the Turkish Straits System in which it discharges. The results of these studies can be found in Özsoy *et al.*(1986, 1988), Ünlüata and Özsoy (1986), Baştürk *et al.*(1986, 1988, 1990) and Latif *et al.*(1989, 1990).

The development of the experimental programme of the present project and its intermediate results have been given in the first (Latif *et al.*, 1992) and second (Özsoy *et al.*, 1992a) progress reports submitted earlier.

The results of the earlier studies on the oceanography of the Turkish Straits system have been published in a number of papers by Ünlüata *et al.*(1986), Latif *et al.*(1991), Oğuz and Sur (1989), Oğuz *et al.*(1990), Özsoy (1990), Özsoy *et al.*(1992b,c) and Beşiktepe *et al.*(1993, 1994).

1.3 Organization of the Report

The plan of the report is as follows: The results of earlier studies pertaining to the present investigation are summarized in Chapter 2. The results of the current velocity, volume flux, and sea-level measurements are examined in Chapter 3. Acoustical backscatter measurements for the detection of the structure of the discharge plumes are described in Chapter 4. The results of the Rhodamine-B tracer experiments are given in Chapter 5. The results of chemical tracer studies are presented in Chapter 6. Discussion and final conclusions are given in Chapter 7.

The present report is organized in three Volumes, with the following contents:

VOLUME 1 - TEXT
VOLUME 2 - TABLES AND FIGURES
VOLUME 3 - CTD AND DYE CONCENTRATION PROFILES

CHAPTER 2

FLUXES OF WATER, NUTRIENTS AND ORGANIC CARBON THROUGH THE BOSPHORUS

2.1 Introduction

The two-layer Bosphorus flows transport materials from the Mediterranean into the Black Sea, and export materials from the Black Sea into the Marmara Sea. Estimates of water, nutrient and carbon fluxes through the Bosphorus are essential for understanding the Marmara Sea budgets as well as the Black Sea budgets. However, the exchanges through the Bosphorus are complicated because of the dynamic variability in these flows. The Bosphorus flows depend on the short term and seasonal variability of the strait dynamics, operating in the full range of possible forcing and flow configurations, *i.e.* blocked flows of the upper and lower layers, short term transients, and seasonal and interannual response to the net water budget of the Black Sea, which in turn is highly variable.

In the case of the Black Sea, the net fluxes of nutrients carried both ways through the Bosphorus are of the same order, and are much smaller than the nutrients introduced by the river Danube alone. On the other hand, dissolved and particulate carbon leaving the Black Sea are much larger than the lower layer inputs.

The above results of earlier studies are discussed in the following, to complement the results of the present investigation.

2.2 A Review of the Bosphorus Exchange Flow Dynamics and Volume Fluxes

The Bosphorus transports can only be quantified by detailed observations, in view of the transient and dynamic nature of the flows through it. Although a number of earlier observations have been made in the past, those made by the Institute of Marine Sciences are the only set of long-term, systematic measurements to date, yielding results to define the hydrochemistry and flow regimes of the Bosphorus and Dardanelles Straits, and the Marmara Sea (Özsoy *et al.*, 1986, 1988, 1992a-c; Latif *et al.*, 1990, 1991, 1992; Oğuz *et al.*, 1990; Ünlüata *et al.*, 1990). The average Bosphorus fluxes are estimated from these data. More recently, current-meter and acoustic Doppler current profiler (ADCP) based

measurements of the fluxes have also been carried out (Latif *et al.*, 1992, Özsoy *et al.*, 1992a-c), as described in Chapter 3.

Based on the long term averages of salinity at the strait entrances and the steady-state mass and salt balances, the average fluxes at the Black Sea end of the Bosphorus (Figure 2.1) have been computed to be $\sim 600km^3/yr$ ($\simeq 20000m^3/s$, outflowing from the Black Sea) and $\sim 300km^3/yr$ ($\simeq 10000m^3/s$, inflowing ino the Black Sea) respectively. These estimates are considerably higher than others given in literature, mainly due to underestimation of the net freshwater input in the previous computations (Ünlüata *et al.*, 1990). The steady-state salt budget of the Black Sea requires that the ratio $Q_{1b}/Q_{2b} = S_{2b}/S_{1b} = 35.5/17.9 \simeq 2$, where Q_{1b}, S_{1b} and Q_{2b}, S_{2b} are the upper (1) and lower (2) layer volume fluxes and salinities defined at the Black Sea entrance of the Bosphorus. The same computations estimate the turbulent entrainment exchange from the lower to the upper layer flow of about $Q_u \simeq 85km^3/yr$ (less than than 25% of the lower layer flow). A somewhat smaller ratio ($< 10\%$) of the upper layer flow is likewise introduced into the lower layer by turbulent entrainment processes. These ratios of entrinment are consistent with other estimates, (*e.g.* Gunnerson, 1974).

The ADCP measured (cf. Table 3.1) average upper layer fluxes are found to be of the same order as the average fluxes computed from mass balances. On the other hand, the lower layer fluxes are found to be much lower than the other estimates. Moreover, these measurements show that the Bosphorus fluxes change significantly, even within a single day.

Tides in the region are insignificant; yet Özsoy *et al.*(1986, 1988, 1990, 1992a-c), Ünlüata *et al.*(1990), and Latif *et al.*(1991) have shown that transience on various time scales, in response to meteorological and hydrological conditions in the adjacent seas, are typical of the exchange flows. Normally, the Black Sea and Mediterranean waters are separated by a density interface which becomes shallower from north to south (Figure 2.2a). Blocking of the flows in either layer occurs during extraordinary, though not entirely infrequent events. The lower layer flow blocking (Figure 2.2b) typically lasts for a few days (Latif *et al.*, 1989, 1991). Likewise, the upper layer flow blocking (Özsoy *et al.*, 1986, 1988 1992a-c, and Latif *et al.*, 1991), during which an anomalous three-layered stratification develops and the salinity is increased in the southern Bosphorus (Figure 2.2c), also lasts for only a few days.

The lower layer flow is typically blocked during the spring and summer months when the net freshwater influx to the Black Sea increases. The ADCP and long term current-meter measurements presented in Chapter 3 also reveal several blocking events.

The upper layer blocking events (identified locally as *Orkoz*), occur in the autumn and winter months, when the surface flow reverses, and the surface salinity increases in response

to the setup caused by southwesterly winds, evident in the earlier data of DAMOC (1971), Gunnerson and Özturgut (1974), and Arısoy and Akyarlı (1990). Long-term measurements of daily salinity and temperature in the Bosphorus (Figure 4) indicate increased surface salinity during these events (Artüz and Uğuz, 1976).

Due to the combination of a contraction and a sill, and the supercritical transitions at these control sections (Figure 2.3.a), the Bosphorus is the foremost example of a strait with *maximal exchange* (Özsoy *et al.*, 1986, Ünlüata *et al.*, 1990). Provided that the reservoir conditions in the adjacent basins are suitable, the existence of two hydraulic controls, by efficiently isolating the mechanics of the strait from the basins, leads to maximal exchange (Farmer and Armi, 1986; Armi and Farmer, 1987). These basic features are confirmed by numerical computations (Figure 2.3.b, after Oğuz *et al.*, 1990). Moreover, when the sill is located nearer to the smaller density basin (relative to the contraction, as in the case of the Bosphorus), the exchanges become assymmetric with respect to barotropic flows and the relative geometrical dimensions of the control sections (Farmer and Armi, 1986). In summary, the Bosphorus responds rapidly to changes in the forcing conditions (net barotropic flow, wind setup, or inverse barometric effects in the adjacent basins), and operates in the full range of weak to strong barotropic forcing in either direction. The nonlinear character of the controlled flows makes its response to these forcings rather complex on time scales of several days to a few years. Curiously, a two-year subharmonic signal can be detected in Figure 2.4, and is not likely to be the result of seasonal meteorological forcing.

The net freshwater inflow into the Black Sea, has large seasonal and interannual variability. Although we do not have reliable information on the variability of the atmospheric components, the river runoff component (Serpoianu, 1973; Özturgut, 1966; Tolmazin, 1985; Bondar, 1989; Bondar *et al.*, 1991) indicates such variability. The Danube river accounts for about 50 % of the total freshwater inflow, and its annual mean discharge, monitored for more than a century shows large natural variations (Figure 2.5). The seasonal changes in the Danube water flux are about ± 30 % of the annual mean (Serpoianu, 1973; Bondar, 1989). In short, the combined seasonal and interannual variations account for a ratio of ~ 3 between the minimum and maximum of Danube flows over a period of several years. More significantly in Figure 2.5, the Danube influx appears well correlated with the sea-level changes on interannual time-scales, as a result of the controls exerted by the Bosphorus.

Motivated by this functional variability of the fluxes, the exchange through the two controls has been studied by Özsoy (1990), through a model modified after Farmer and Armi (1986) to include Black Sea storage, finite depth at the contraction, and time-dependent barotropic forcing. Multiple-valued (inviscid) or nonlinear (frictional) solutions with seasonal to interannual responses were found (Figure 2.6). These solutions exemplify the expected differences between fluxes based on average sea-level or net flux values and those computed by averaging the time-dependent seasonal variations. This is consistent with the observed variability of the Bosphorus fluxes and flow regimes.

2.3 Nutrient and Organic Carbon Fluxes

The Bosphorus Strait, which permit the exchanges of the brackish and salty waters with the associated conservative and non-conservative chemical properties between the Black and Marmara Seas, has been used as a receiving water environment for the domestic and industrial wastewaters of the İstanbul Metropolitan Area (IMA). Because of heavy industrialization and drastic population increases in the area during the last 30 years, the IMA appears to have been the major pollution source for the the Sea of Marmara. Therefore, comparison of the chemical loads discharged from IMA with the exchange fluxes by the Bosphorus two-layer flows would lead the policy makers to develop a technically and a financially applicable waste water management programme for IMA so as to recover the deterioted Marmara Sea ecosystem. On the other hand, the implementation of such a programme is closely dependent on a through understanding of the principal hydrochemical properties of the the Turkish Strait System whose surface waters are influenced by both the polluted Black Sea inflow and direct wastewater discharges from the catchment area of the basin.

Since profound changes have occurred in the Black Sea ecosystem during the last two decades, the most dramatic, on the northwestern shelf, ecological properties of the Marmara Sea are very likely to have been altered by the Bosphorus surface flow. Because the brackish water leaving the Black Sea through the Strait evolves from alongshore currents from the northwestern shelf of the Black Sea whose waters, being seriously polluted with man-made chemicals brought in by riverine (mainly the Danube) discharges, possess modified biochemical properties relative to the open Black Sea surface waters. Therefore, the nutrient and organic carbon exports from the Black Sea through the Bosphorus, which are possibly too small to influence the budgets for the whole Black Sea system, are very likely to be critical to budget estimates for the Marmara Sea, whose upper-layer water is renewed at least twice a year by the Black Sea inflow (Ünlüata *et al.*, 1990; Beşiktepe, 1991). Therefore, it is rather difficult to assess contribution of the land-based pollution loads from İstanbul to the modification of the Marmara Sea ecosystem relative to that of the input from the Black Sea, which have increased during recent decades.

On the other hand, during their residence time of six to seven years in the Marmara Sea, the saline Mediterranean waters entering through the Dardanelles, initially poor in nutrients and almost saturated with oxygen, become enriched 10-fold with dissolved inorganic nutrients, though also becoming impoverished in dissolved oxygen to the levels of 30-50 μM. The Mediterranean waters with their modified chemical properties eventually leave the Marmara basin through the Bosphorus undercurrent towards the Black Sea; some fraction of this flow with the associated chemical properties is returned to the Marmara surface layer by mixing in the Bosphorus region.

In this context, systematic chemical data collected in the Bosphorus region between 1986 and 1992 by the METU-IMS group have been examined by Polat and Tuğrul (1994) in detail so as to give reliable estimates of the total annual fluxes of nutrients (nitrogen and phosphorus) and organic carbon exchanging between the Black and Marmara Seas through the two-layer flows in the Bosphorus.

2.3.1 Nutrients and Organic Carbon in the Outflow from the Black Sea

The concentrations of the dissolved inorganic nutrients and dissolved organic carbon in the Black Sea outflow show significant variations with season (Figure 2.7). Below the brackish waters of the Black Sea at northern entrance of the Bosphorus, the nutrient concentrations increase with depth in the more saline waters flowing towards the Black Sea. Systematic data depicted in Figure 2.8 demonstrate that the inorganic nutrient content of the outflow from the Black Sea increases at least ten-fold from autumn to winter and then decreases again to trace levels in summer. The nitrate (actually nitrate + nitrite) concentration rises to the levels of as high as 4.5-7.5 μM in winter and diminishes to trace leves (<0.1-0.2 μM) in the summer-autumn period. Significantly high winter concentrations imply that a significant fraction of the inorganic nutrients introduced both by the major rivers and by the wastewater outfalls to the northwestern coastal margin of the Black Sea may reach as far as the Bosphorus without being consumed by photosynthesis under severe winter conditions (Polat and Tuğrul, 1994). Similarly large nitrate values have been reported for the Romanian surface coastal waters (S>15 ppt) in winter. Dissolved inorganic phosphorus (DIP; the so-called reactive phosphate) concentrations also exhibited marked seasonal varitions in the Bosphorus surface flow, from <0.05 μM in the July-October period to the leves of 0.3-0.6 μM in winter. The annual means estimated from the long-term data are 1.6 $\pm$1.6 μM for nitrate and 0.18 $\pm$ 0.18 μM for DIP, which are very consistent with those estimated by Orhon *et al.*(1994) for the 1987-1989 period, using the METU-IMS data from the Bosphorus region. Based on limited data from the western Black Sea, the annual mean of the ammmonia concentration has been estimated as 0.5 μM for the outflow.

Particulate organic nitrogen (PON) concentrationss in the Black Sea outflow were observed to vary from 1.0 μM in summer to 4.8-5.0 μM during late winter – early spring between 1991-1992. The particulate phosphorus (PP) concentrations showed a similar seasonality, but remaining always in the range of 0.1 to 0.2 μM. The estimated annual means are 2.4 μM for PON and 0.17 μM for PP, yielding a PON:PP ratio of nearly 14. Estimates of the annual averages of dissolved organic phosphorus (DOP) and dissolved organic nitrogen (DON) concentrations are 0.15 μM and 18 μM, respectively (Polat and Tuğrul, 1994). One should note that a large fraction of DON in the outflow is composed of biologically less labile DON of primarily terrestrial origin, being discharged to the northwestern shelf waters by the major rivers. The dissolved organic carbon (DOC) contents of the outflow show only small seasonal changes relative to the concentrations of biologically labile nutrients

and POC. The depth-averaged DOC concentrations varied seasonally from 167 μM to 217 μM, yielding an annual average of 192 μM for the 1987-1992 period. Particulate organic carbon (POC) ranged from 10 μM to 40 μM, with an annual mean of 21 μM (Polat and Tuğrul, 1994). Larger DOC concentrations always appearered during late winter – early spring bloom in the soutwestern Black Sea.

As shown in Table 2.1, the total phosphorus (TP), 0.50 μM, is composed of similar levels of DIP, PP and DOP concentrations on the annual basis. In fact, their contribution to TP varies seasonally; for example, DIP dominates the TP in winter, but during bloom PP being major constituent of TP. The TN computed from the mean DON, PON and DIN data is 22.5 μM. The biologically labile fraction (DIN+PON) constitutes about 20 % of the TN and the rest consists of less labile DON. Nevertheless, because of large and continuous nutrient inputs by the major rivers to the Black Sea, the brackish waters of the Black Sea outflowing through Bosphorus may contain concentrations of biochemically labile dissolved and colloidal DON of photosynthetic origin amounting to at least 5-20 % of the total DON; the higher fractions appear during periods of high primary productivity (Polat and Tuğrul, 1994 and references quoted therein). The labile fraction of DON (including colloidal fraction, < 1.0 μm) contributes to the new production in the Marmara Sea, whilst the biologically resistant DON reaches the Mediterranean several months later through the Dardanelles Strait. High ratios of both TOC and TN to TP (TOC:TN:TP = 425:45:1) are due to large DOC and DON input by rivers to the western Black Sea surface waters, some part of which eventually outflows though the Bosphorus. The POC:PON:PP ratios of the outflow are about 122:14:1, consistent with the Redfield ratio of 16 for the oceans.

Detailed examination of the systematic data data revealed that the concentration of biologically labile nitrogen (DIN+PON) in the Black Sea outflow increased to the levels of 7.7-8.5 μM (mean: 8.2 μM) in the winter-early spring (December-March) but then decreased steadily to 1.3-3.0 μM (mean: 2.2 μM) during the late spring-late autumn period. However, seasonal changes in the TP concentrations of the outflow, ranging between 0.29 and 0.65 μM, were less than in labile nitrogen. Thus, even if the Black Sea outflow in the Bosphorus were constant with time (in fact, it is not), quantities of of the biologically labile nitrogen (DIN+PON) and TP exported from the Black Sea during the winter - spring period are very likely to exceed at least 2-3 times the chemical fluxes during the summer-autumn period.

For the winter-spring and summer-autumn periods, the mean POC concentrations were 25.8 μM and 15.8 μM respectively, these concentrations deviating by about 25 % from the estimated annual mean of 21 μM. On a total concentration basis, the annual variation of the TOC (possibly TN) concentrations in the outflow, however, is of the order of 10 % because these total values are primarily dominated by the biologically less labile DOC (and possibly DON) of terrestrial origin.

2.3.2 Nutrient and Organic Carbon in the Outflow from the Sea of Marmara

Simply put, the Sea of Marmara is a two-layer system separated by a sharp interface, generally formed between 15 and 30m depths; the surface layer is occupied by brackish waters of Black Sea origin whilst the lower layer below the interface contains saline waters of Mediterranean origin. Photosynthesis being limited to the upper layer including the interface between 15 and 30m, seasonal changes in nutrient and organic carbon concentrations in the chemically modified Mediterranean water flowing out through the Bosphorus are much less than those in the waters leaving the Black Sea (see Figure 2.7), permitting one to compute depth- averaged values of the Marmara outflow quite safely. Data collected between 1986 and 1992 show that, throughout each year, nutrient concentrations in the saline Marmara Sea waters entering the Bosphorus have ranged from 7 to 12 μM (annual mean: 9.50.86 μM) for nitrate and from 0.7 to 1.2 μM (annual mean: 1.01 $\pm$ 0.10 μM) for phosphate. The ammonia concentration is as low as 0.2 μM in the outflowing saline waters and certainly much less than the corresponding nitrate concentration.

In the outflow from the Sea of Marmara, depth-averaged PP and PON concenrations vary seasonally between 0.27 and 0.60 μM for PON and between 0.04 and 0.06 μM for PP, with the annual averages of 0.41 and 0.05 μM, respectively. The concentrations of DOP estimated from the differences between TP and (DIP+PP) are always less than 0.1 μM, suggesting an annual mean of 0.05 μM. Though DON has yet to be measured in the outflow, a mean value of 3.0 μM has been estimated basing on the DON, DOC data and DOC:DON ratios for the saline waters of the western Mediterranean and Marmara Seas. The DOC concentrations in the outfow ranged from 65 to 80 μM between 1986-1992, as appearing from typical profiles (cf. Figure 2.7). T. The estimated annual average of DOC (73 μM) is much greater than the POC concentrations varying seasonally between only 2.5 and 9.1 μM, with an annual average of 5.2 μM for the outflow.

The annual means of the various forms of nutrients and of organic carbon estimated for the Marmara outflow are also displayed in Table 2.1. DIP, DIN and DOC constitute the major fractions of the total nutrients and organic carbon in these saline waters. The computed TOC:TN:TP molar ratios are 70:12:1, whereas the IN:IP ratio is about 9.6, less than the Redfield ratio. The TP content of the Marmara outflow is twice that of the inflow from the Black Sea. A similar feature is encountered for TN when labile fraction (about 10 %) of DON is included in estimating TN ratio of the exchanging waters; but a contrary view appears when the less labile DON, too, is included.

2.3.3. Nutrient and organic carbon exchanges between the Black and Marmara Seas through the Bosphorus

Long-term current measurements in the Bosphorus are very limited to estimate the exchange fluxes of nutrients and organic carbon through the Bosphorus on a seasonal time

scale. Therefore, the average concentrations of chemicals (Table 2.1), together with the volume fluxes of the flows in the Bosphorus (Figure 2.9.a), assuming these are constant on a yearly time scale, have been used to calculate the annual quantities of the total nutrients and organic carbon exchanged between the Black and Marmara Seas. The flux estimates depicted in Figures 2.9b-d, represent the order of magnitude of the annual exchanges between the Black and Marmara Seas and should be used cautiously in examining short-term exchanges in the Bosphorus, due to seasonal fluctuations in both the valume fluxes and concentrations of biologically labile chemicals of the flows.

Figure 2.9b shows that about 9,000 tons of TP per year are imported to the the upper layer of the Marmara Sea from the the Black Sea. Because of the entrainment of the DIP- rich water originating in the saline waters of the Marmara Sea, by the interface in the Bosphorus Strait, the annual TP input to the Marmara Seas rises to about 12,000 tons, about 50 % of which is composed of DIP (Polat and Tuğrul, 1994). We should note that the exchange flux estimates of Uslu *et al.*(1994) are based on data of dissolved inorganic nutrients obtained in the exchanging waters of the adjacent seas. They did not consider the dissolved/particulate organic nutrients, which constitues the major fraction of the total nurients in the brackish surface waters leaving the Black Sea especielly during the productive seasons as discussed extensively by Polat and Tuğrul (1994). Therefore, their esimates of phosphorus fluxes represent only the DIP fraction, which, according to the findings of Polat and Tuğrul (1994), constitutes merely 50 % of the TP import to the Marmara Sea from the Black Sea, including the gain from the Boshorus counterflow. As also shown in Figure 2.9b, the TP exported from the Black Sea is nearly compensated by the total input (9,600 tons y^{-1}) from the Sea of Marmara. The TP exported from the Marmara Sea is consistent with the estimate of Orhon *et al.*(1994) because DIP constitutes the major fraction (about 90 %) of the TP in the Marmara outfow.

Estimated nitrogen fluxes (Figure 2.9c) indicate the TN import to the Marmara Sea from the Black Sea (approximately 190,000 tonsy^{-1}) to be three times the input (61,000 tons y^{-1}) by the export from the Marmara Sea through the Bosphorus. But a contrary view has been drawn by Orhon *et al.*(1994) due to comparison of inorganic nitrogen fraction only, which is minor in the Black Sea outflow but the major constituent of TN in the outflow from the Marmara Sea (see Table 2.2). Biologically labile nitrogen (DIN+PON) constitutes approximately 25 % of the TN fed into the Marmara surface layer and 66 % (primarily nitrate) of TN import to the Black Sea by the Bosphorus underflow; the remainder of the TN consists of less labile DON. Comparison of the (DIN+PON) and TP exchange fluxes in the Bosphorus estimated by Polat and Tuğrul (1994) suggests that biochemically labile nutrients exported from the Black Sea is compensated by the Bosphorus counterflow principally as nitrate and reactive phosphate (DIP).

Estimates of TOC exchage fluxes displayed in Figure 2.9d indicate a net input of organic carbon into the Marmara Sea from the Black Sea through the Bosphorus (difference between the TOC influx and outflux at the exit to the Black Sea). The annual TOC import to the Marmara Sea is about $1.5x10^6$ tons, which is about 4 times larger than the export ($3.5x10^5$ tons) from the Marmara Sea to the Black Sea. The annual fluxes of POC, constituting a minor fraction (about 10 %) of TOC in the flows, is about $1.5x10^5$ tons for the inflow from the Black Sea whereas the export from the Marmara is on the order of $3.0x10^4$ tons. The TOC exchange fluxes of Orhon *et al.*(1994) were underestimated by 10-30 % relative to those of Polat and Tuğrul (1994), who obtained the TOC in the flows from the sum of the blank corrected DOC data and separate POC measurements. Put simply, biochemically resistant dissolved organic matter (DOM, involving colloidal fraction) introduced into the Marmara surface waters from the Black Sea reaches the Aegean Sea through the Dardanelles to the southwest of the Marmara, while the particulate organic matter (involving biologicaly labile organic carbon and nutrients) oxidized in the upper layer contribute to the net primary production, but fraction sinking the lower layer (sub-halocline waters) contributes to inorganic nutrient pool, with a concomitant decrease in dissolved oxygen content of the lower layer.

2.3.4 Comparison of the Exchange Fluxes through Bosphorus with the Pollution Load from İstanbul

According to estimates of Orhon *et al.*(1994), approximately $8.9x10^4$ tons of TOC, $2.0x10^4$ tons of TN and $3.3x10^3$ tons of TP per year are currently discharged into the Marmara Sea from the İMA (see Table 2.2). About 50 % of the total discharges from the IMA enters directly the Bosphorus surface flow and the Bosphorus-Marmara Junction (BMJ) region. At present, only 20 % of the total discharges from the IMA are given into the lower layer of the Bosphorus by the Yenikapi outflow. Close examination of the exchange fluxes between the Black and Marmara Sea and the land-based pollution loads compiled in Table 2.2 reveals that the present TP input from the Black Sea is about 2.8 times the annual load originating from the IMA, but 4.2 times that discharged into the Bosphorus Strait and BJM-region. The ratio of the Black Sea input to the total of TP from İstanbul was underestimated by Orhon *et al.*. (1994), who utilized only the dissolved inorganic forms of phosphorus (DIP) and nitrogen (DIN) existing in the seawater to compute the total nutrient (TP and TN) outflux from the Black Sea. Therefore, their estimate for the TN outflux from the Black Sea is also much less than that given by Polat and Tuğrul (1994). As clearly seen in Table 2.1, the disssolved inorganic nitrogen and phosphate compounds constitute the minor fraction of TP and TN in the surface waters of the Black Sea; during the productive seasons, its contribution decreases further (see Figure 2.8). The TN input from the Black Sea to the Marmara Sea, basing on the TN (DIN+PON+DON) data given in Table 2.2 and water flows dispayed in Figure 2.9a, is at least 9 times the TN load from the IMA. When only the labile fraction of DON available in the seawater is

included in determining the biologically labile TN content (DIN+PON+10 % of DON) of the Black Sea, the ratio of the TN input of Black Sea origin to the total load from from the IMA would drop to nearly 2.5; but, the ratio would rises to 4.7 if only the pollution load given to to the Bosphorus and BMJ-region is considered. Similarly, TOC input from the Black Sea is much larger than the total load originating from İstanbul (see Table 2.2), in agreement with the findings of Orhon *et al.*. (1994). However, Polat and Tuğrul (1994) have emphasized that the major fraction of TOC (POC+DOC) existing in the outflowing waters of the Black and Marmara Seas through the Bosphorus is resistant to bacterial decay on a weekly or monthly time-scale. A major fraction of POC in the productive surface waters of the Black Sea, which comprises about 10 % of TOC in the surface waters, may be assumed to be biologically labile whereas about 5-20 % of DOC to be in labile form, depending on the rate of DOC release during the primary production varying with season. Thus, about 15-20 % of TOC in the outflow from the Black Sea may be assumed to be biological labile during its stay in Marmara Sea. When the labile TOC in the outflow is compared with the land-based load from the, the ratio would range between 2.5- 3.4. Put simply, the annual inputs of biochemically labile fraction of nutrients and organic carbon to the Marmara Sea from the Black Sea are at least 2-3 times the total pollution loads from İstanbul. 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.

Table 2.2 also permit us to compare the chemical export from the Marmara Sea through the Bosphorus with the pollution loads from the IMA. The TP input to the Black Sea from the Marmara Sea is nearly 3-fold the total load originating from the IMA; but it exceeds at least 4 times the TP discharged into the Bosphorus and BMJ-region. Similar conclusions can be drawn for the TN and TOC parameters, basing on the input data given in Table 2.2. However, we should note that the TOC exported from the Marmara Sea is principally in the refractory form because TOC cencentrations of the salty Mediterranean waters entering the Marmara Sea is as low as 60-70 μM, showing little seasonal fluctuations which are not distinguished from the analytical bias. If only 10 % of TOC in the the Marmara Sea outflow is assumed to be biodegradable on a weekly or monthly time-scale, the ratio of natural TOC export from the Marmara to the total TOC load from the IMA would as low as 0.4; but it would be slightly raised to 0.7 when the TOC load given into the Bosphorus and BJM-region is considered only. Therefore, the deep outfalls of wastewaters from İstanbul, with the present TOC loads, are expected to cause critical oxygen depletions in the Marmara lower layer waters (which are currently poor in dissolved oxygen), especially in the regions of discharges, where the general circulation is relatively weak during the stratified seasons. The inorganic N:P ratio in the outflowing waters of the Marmara Sea is about 10, less than the Redfield ratio. Therefore, nitrogen-rich waste discharges to the Marmara Sea ecosystem seem to facilitate the primary production in the surface layer.

However, bio-assays performed in the western Izmit Bay indicated both phosphorus and nitrogen limitations on the uptake rate of inorganic carbon by phtoplankton, suggesting further regional basis bio-assays and oceanographic studies to define environmental factors and processes controlling the algal growth with season.

CHAPTER 3

EXCHANGE FLOWS THROUGH THE BOSPHORUS

3.1 Volume fluxes

Volume flux measurements were made utilising an acoustic Doppler current profiler (ADCP) mounted in the hull of the ship. The north and east components of the velocity were measured using the bottom track mode to account for the ship velocity. For determining the velocity structure across the width of the strait the ship moved at a speed of 4 - 5 knots from one bank to the opposite side. Velocity ensembles were obtained at 30 seconds interval. The location of the ship at the beginning of a transect was determined by a satellite navigator on board. The velocity data were integrated over the section to determine the discharge. In addition to transects, velocity profiles were also measured while the ship was staying in a fixed position at station.

The computation of fluxes from the ADCP measurements suffers from loss of data from the top and bottom of the water column and near the sides of the strait. The transducers of the ADCP are mounted in the hull of the ship, 4 meters below the sea surface. In addition, the ADCP requires at least two meters between the depth of the first first reliable measurement and the transducers to establish communication, thus the first data are obtained 6 m below the surface. In the southern end of the Bosphorus, the upper layer thickness is of the order of 15 to 20 meters, and the speed is maximum near the surface, therefore the data loss due to this source is particularly severe in this region. The loss of data near the bottom occurs because the ADCP can not resolve the velocities below about 75 % of the depth. This region is important in determining the lower layer flux in the northern reaches of the strait. In particular, in cases where the lower layer is thin, the error in determining the lower layer flux is high.

A further loss of data occurs in the region between the side of the strait and the position of the ship just before it has to turn away. This loss is particularly important in the narrower sections of the strait where strong currents exist close to the shores.

The computation of the fluxes attempts to take into account the above mentioned deficiencies in the data by extending the velocity profiles to the surface and the bottom using the last measured values in these regions. To account for the loss near the sides, the profile closest to the shore were integrated over an extended horizontal distance until the shore.

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In spite of these corrections, it was observed that significant variations in the fluxes along the strait existed in many of the surveys. These variations are due to the unsteady nature of the flows in the strait in response to a varying sea level difference between the two ends of the strait. Measurments of the sea level have been initiated by the Institute in September 1993. Sea level data are not avilable for determining the sea level difference during the ADCP survyes prior to this date. Howerver, sea level measurements have been made at Erdek in the Sea of Marmara by HGM for several years. It is realised that the sea level difference across the two ends of the Bosphorus, and not just the sea level in either the Black sea or the Sea of Marmara, is the determiming parameter for the flows in the strait, however, an increasing sea level at Erdek must imply a decrease in the sea level difference, and vice versa. Hence, the Marmara (Erdek) data may be utilised in explaining the observed variation of fluxes in surveys in which measurements were carried out on consecutive days.

3.1.1 Results of the ADCP surveys

The average upper and lower layer fluxes for all the surveys are summarized in Table 3.1. The average has been approximated from plots of fluxes for each survey.

The minimum value of flux in either layer is zero, representing blockage of the layer. Blockages of the lower layer were observed during surveys in March and May 1992, and in February . An upper layer blockage was observed during the December 1993 survey. The maximum observed value of the upper layer flux was 50,000 m^3/s, on 10 March 1992, and the maximum for the lower layer was 15,000 m^3/s, on 2 September 1992, and on 5 March 1993. The upper layer flows are generally high in the winter and spring months and low in September and October, in agreement with the inflows from the major Black Sea rivers. The average of all the upper layer flows in Table.3.1 is 20,000 m^3/s and the average lower layer flow is 5,000 m^3/s.

In the following, data obtained during the cruises since April 1991 are presented. Figure 3.1 shows the station locations and Figure 3.2 the adcp transect locations for all ADCP and CTD surveys. In order to avoid repetition, location maps for individual surveys are not presented; these may be found in reports submitted earlier.

1 April 1991

The survey was carried out at a time when the sea level had stabilised after falling for the previous three days, Figure 3.3. The upper layer flux was approximately 25,000 m^3/s, Figure 3.4. The lower layer flux was 3,000 m^3/s in the souththern part of the strait, and about 200 m^3/s in the northern half.

21 August 1991

This survey was also carried out at a relatively stable peroiod in the sea level, Figure 3.5. The upper layer flux, Figure 3.6, varies between 15,000 m^3/s and 20,000 m^3/s along the strait, while the lower layer flux is about 4,000 m^3/s.

2 October 1991

The sea level record and the fluxes for this survey are shown in Figures 3.7 and 3.8. In this survey, the lower layer flow was higher than the upper layer. The upper layer flow was about 10,000 m^3/s, while the lower layer flow was about 4,000 m^3/s.

29 October 1991

During this survey, the sea level at Erdek underwent a transition: it had been rising for about a day and a half, and began to decrease just about the time the ADCP survey started, Figure 3.9. The fluxes are shown in Figure 3.10. During the first part of the survey, in the southern half of the channel, the upper layer indicates a gradual decrease, while the lower layer decreases gradually, both consistent with a rising elevation at the southern end of the strait. In the northern half of the strait, north of B8, the trends are reversed, indicating the influence of the decreasing sea level.

December 1991

Five surveys were carried out during this cruise. As seen in Figure 3.11, the first three surveys were carried out during a period when the sea level at Erdek was increasing and the last two when it was decreasing. The velocity profiles are shown in Figures 3.12 - 3.16, and the fluxes in Figures 3.17 -3.21. The upper layer flux for the first survey, on 19 December, which covered three stations at the southern exit, was about 13,000 m^3/s, and the lower layer flux was about 5,000 m^3/s, Figure 3.17. The fluxes for the following day, 20 December, are given in Figure 3.18. The upper layer flux is about 17,500 m^3/s, while the lower layer flux is about 3,000 m^3/s. In the third survey, on 21 December, the lower layer flux increased to about 11,000 m^3/s, while the upper layer flux decreased to about 5,000 m^3/s. This change in the fluxes is attributed to the continuing rise in Erdek sea level. The next survey was carried out two days later, on 23 December. The sea level had begun to fall approximately one day before the start of the survey. The fluxes, Figure 3.20, show a continous increase in the upper layer flux and a decrease in the lower layer flux as the survey progessed north toward the channel. These changes are consistent with the decrease in sea level at the southern end. The upper layer flux increased from about 5,000 m^3/s to 13,000 m^3/s, while the lower layer flux decreased from 11,000 m^3/s to about 5,000 m^3/s during the course of the survey. The following day, 24 December, the same trends continued in the fluxes, Figure 3.21. The upper layer flux reached a value of about 18,000 m^3/s,while the lower layer decreased to about 5000 m^3/s.

March 1992

In this survey, which was carried out in conjuntion with a negative pulse experiment, a relatively long episode of the blocking of the upper layer was documented. The sea level data, Figure 3.22, shows that the sea level was on a generally decreasing trend before the survey. The sea level reached its lowest value between 9-10 March and then began to increase. The first survey was carried out on March 5. At that time, the upper layer flow was 22,500 m^3/s, and the lower layer flow was 2,500 m^3/s.

The velocity profiles from the ADCP measurements at stations for March 5 are shown in Figure 3.23. It is seen that the upper layer flow occupies almost the entire depth of the strait in the northern half. The lower layer is observed within the last 10 m in most of the stations, with the exception of stations near the Marmara exit. The lower layer is, in fact, blocked at the northern sill, about 3 km north of Sta. K0.

Subsequent surveys were carried out on March 8,9,10,11,12,13 and 14. These surveys covered a limited number of stations to monitor the position of the lower layer and the flow in the upper layer. In the March 8 survey, it was observed that the lower layer was blocked at B5, near Ortakoy. The blockage did not receede further south from this location in the following days. The velocity profiles, Figure 3.24, for March 10 are representative of the conditions during the blocking period. In the March 12 survey, it was observed that the lower layer had started to progress northwards. A survey covering the strait was carried out on March 14; in this survey the two layer flow had become established. The velocity profiles, Figure 3.25, show the lower layer flow was exiting beyond the sill. The upper layer flux in this survey was 15,000 m^3/s and the lower layer flux 4,000 m^3/s. The volume fluxes for all the surveys in this cruise are shown in Figures 3.26-3.32.

The salinity transect for the 5 March survey, Figure 3.33, shows that the thickness of the upper layer at the northern sill is about 55 m. The interface is quite sharp untill the constriction section between stations B6 and B8. The thickness of the upper layer decreases rapidly from this region till the southern exit. The upper layer is about 10 m at B2 and about 5 m at the exit. Conditions during the blockage are shown by the transect for 10 March, Figure 3.34, which shows the Black Sea water occupying the strait from the northern end untill the constriction region where a strong front is seen. After the resumption of the lower layer flow, the depth of the interface at the sill was 50 m, Figure 3.35, and the interface had increased in thickness throughout the strait.

May 1992

A series of three surveys, between 14-18 May was carried out in this cruise. The sea level during the first survey was in transition from a rising to a falling trend, in the second survey the sea level continued to fall and in the third survey it was rising again. The lower layer flow was blocked during 14-17 May. The variability in the upper layer flux closely

reflects the changes in the sea level. The first survey was carried out on 14 May. The sea level, Figure 3.36, at the beginning of the survey was rising and began to decrease at about the time the survey had been half completed. The velocity profiles, Figure 3.37 -3.39 indicate speeds of about 150 cm/s in the upper layer in most of the strait on 14 May. On the following day the velocities decreased in the southern part of the strait, and on the third day the upper layer velocities decreased further, while the blockage of the lower layer ceased. The upper layer flux, Figure 3.40, shows a gradual decrease from the southern end of the strait till the middle, and then a gradual increase untill the northern exit. This is consistent with the initial rise and subsequent fall of sea level which took place during the survey. On the following day, the sea level continued to fall and the upper layer flux consistently increased from about 20,000 m^3/s at the southern end of the strait to about 40,000 m^3/s at the northern exit,Figure 3.41. In the third survey, carried out on 18 May, the upper layer flux had decreased to about 20,000 m^3/s all along the strait,Figure 3.42, and the lower layer flow had resumed, both consistent with the rising sea level before as well as during the survey.

The velocity data from the moored current meter at Anadolu Kavağı is consistent with the changes observed in the lower layer during the three suveys in this cruise. A portion of the velocity record is shown in Figure 3.43. The speed was about 8 cm/s during the survey on 14 May. On 15 May the speed was 1.5 cm/s, which in fact is the constant offset in the Aanderaa current meter conversion formula, and hence the speed was zero on 15 May. The speed increased to about 28 cm/s on 18 May. The similarity between the bottom velocity variations and the sea level at Erdek (Figure 3.43) during the same period is remarkable. High lower layer velocities correspond to high sea level and vice versa, as expected.

The salinity transects for the three surveys are shown in Figures 3.44-3.46. The interface is at about 50 m in the May 14 and May 15 surveys, and has risen to about 40 m in the May 18 survey.

August - September 1992

Five surveys, between 28 August and 2 September, were carried out during this cruise in conjuntion with a dye tracing experiment. The upper layer flux, as seen in Table 3.1, decreased from 17,000 m^3/s about 3,000 m^3/s, while the lower layer flux increased 5,000 m^3/s to 15,000 m^3/s during the cruise. The lower layer flux was greater than the upper layer flux during the last three surveys.

The sea level at Erdek, Figure 3.47, was on a rising trend before the cruise and continued to rise untill near the end of the surveys. The velocity profiles, Figures 3.48-3.53, show a continuous increase in the lower layer, and a decrease in the upper layer velocities during the period of the cruise. The fluxes are shown in Figures 3.54-3.58. During the first survey, Figure 3.54, the upper layer flux was about 17,000 m^3/s and the lower layer flux about

5,000 m^3/s. The lower layer flux continued to increase and exceeded the upper layer flux on August 31, Figure 3.56. The uneven distribution of the upper layer fluxes in this survey indicates that the effect of the increasing sea level at the southern end of Bosphorus had not influenced the stations in the northern half of the strait at the time. The upper layer flux in the following survey, on 1 September, shows a more uniform distribution along the strait, Figure 3.57, while the lower layer flux increases towards the north, and is greater than the upper layer flux. On the last survey, on 2 September, the upper layer flux, while still less than the lower layer flux, indicates a slow increase towards the northern end of the channel, Figure 3.58.

While the changes in the fluxes during 28 August - 1 September are in agreement with the increasing sea level at Erdek, the reason for the high lower layer flux during the last survey when the sea level was decreasing is that this survey was carried out about 18 hours after the sea level began to fall and the velocities at the northern end of the Bosphorus were still high. There is, in fact, a slight decrease in the lower layer flux and a small increase in the upper layer flux from B13 to B15, Figure 3.58. The velocity record from the moored current meter at Anadolu Kavağı for 30 August - 3 September is shown in Figure 3.59. The lower layer velocity, near the bottom was about 28 cm/s, close to the maximum which occured near midnight of 2 September.

Salinity transects for the surveys are given in Figures 3.60-3.64. The salinity interface rises progressively from the beginning to the end of the cruise, consistent with the increasing lower layer flow. It is aloso seen that the interface is quite thick in all the transects; in the northern part of the strait its thickness is about 20 m. Of particular interset is the salinity transect for 2 September, Figure 3.64, in which the northern exit of the Bosphorus and the adjoining shelf region was covered. The station locations for this survey are shown in Figure 3.65. The Mediterranean water was followed to approximately 12 km from the end of the strait; its thickness at that location, was about 15 m.

11 February 1993

During this survey, strong upper layer flow existed in the strait, while the lower layer flow was blocked. Sea level data for Erdek for 1993 are not available at this time. The velocity profiles, Figure 3.66, show that the southward flow exceeded speeds of 150 cm/s in most of the strait. The profiles also show that the Mediterranean inflow enters at about mid-depth and proceeds till the constriction region, to B6. A return flow of the Mediterranean water is obseved near the bottom of the strait. The upper layer flow in the whole channel was approximately 45,000 m^3/s, Figure 3.67. The salinity transect, Figure 3.68, also shows the upper layer to be blocked at B6, in the constriction region. The sharp interface at the southern exit, stations B0A - E2, imply little mixing between the layers. The return flow near the southern exit can not be identified in the salinity transect, as the entering and the leaving water have the same proerties.

March 1993

A dye tracing experiment was carried out during this cruise. Surveys were carried out daily from 3 March to 7 March. The velocity profiles, Figures 3.69-3.73, indicate that the flows underwent extreme changes in the first three days. The fluxes are shown in Figures 3.74-3.78. The upper layer flux was about 22,500 m^3/s on the first day; it decreased to a near blockage situation on the second day, and on the following day increased approximately to the same value, 20,000 m^3/s. The lower layer went through an opposite cycle: its flux increased from approximately 2000 m^3/s on the first day to about 15,000 m^3/s on the second day and decreased to about 3000 m^3/s on the third day. The following day, 6 March, the upper layer flux increased to 26,000 m^3/s, and the lower layer flux was 1,000 m^3/s zero. Fluxes were measured at two transects in the constriction region on 7 March, and were approximately the same as on 6 March.

The changes observed in the fluxes are reflected as changes in the thicknesses of the two layers and the sharpness of the interface in the salinity transects, Figures 3.79-3.81. On 3 and 5 March, during the periods of high upper layer flow, the upper layer has a thickness of about 50 m in the northern exit region of the strait, and the interface is relatively sharp, indicating little mixing between the layers. On 4 March the upper layer thickness has decreased by about 15 m to 35 m, and the interface is more diffuse and thicker, indicating increased mixing between the two layers, which occurs when the lower layer flow is high.

December 1993

Three surveys were carried out in this cruise, between December 17 - 19, in conjunction with a dye tracing experiment. Water level recorders at Anadolu Kavağı and Fenerbahce were in operation. Figure 3.82 shows the sea level data for the period of the surveys and their duration. (The sea level recorder's clocks are set to GMT, thus there is a two hour difference between the local time and the time on the sea level difference plots for December. This difference has been accounted for in the plot.)

The station velocity profiles are given in Figures 3.83-3.86. During the December 17 survey the sea level difference was -18 cm. Consistent with this negative gradient, the upper layer was blocked through out the entire strait. The northward velocity was between 80 cm/s and 100 cm/s at almost all the stations. In the surveys on December 18-19, carried out between December18, 09:00 and December 19, 03:00, the flow is still to the north, but the velocities are lower. The last two surveys were carried out after the sea level had started to decrease. The resumption of the upper layer flow and the decrease in the lower velocities in the 19 December survey, Figure 3.86, demonstrate the rapid adjustment of the flow to the change in sea level.

Volume fluxes were measured at B5 and B8 on December 18. The upper layer flux was 20,000 m^3/s, and the lower layer flux was zero, Figure 3.87.

The salinity transect for 17 December, Figure 3.88, shows that the Mediterranean water has occupied the strait till B15. The surface salinity is about 25 ppt. On 18 December 18, the Black Sea water has penetrated till B11,Figure 3.89. A front between the inflow from the Sea of Marmara and the Black Sea water is seen at B6-B7 in the constriction region in the upper layer. The front has diasappeared in the following survey, Figure 3.90, which was conducted about four hours later. This again indicates the quick adjustment of the flow to sea level changes. The upper

3.2 Moored Current Meter Measurements

Long term current measurements were carried out in the northern end of the Bosphorus bottom layer using moored current meters in the vicinity of St. B14, near Anadolu KavağıÀanderaa RCM4 recording current meters, having temperature and conductivity sensors in addition to speed and direction, were used. The current meters were deployed inside a cage weighted by concrete slabs at the bottom. A rope for recovery from the cage was tied to a structure on shore. The current meter was about 1.5 m above the bottom, the total water depth at the site being about 65 m. A major problem was fouling of the rotor by floating marine plants and debris, resulting in the loss of a great deal of velocity data. In later deployments, two current meters were installed in the cage, one without a directional vane, due to lack of room for free rotation of two vanes in the cage. The comibnation of data from such a setup resulted in a continuous record from December 1991 to September 1992. Another similar deployment, between August 1992 and September 1993 resulted in velocity data for only three months due to early fouling of the rotor.

The hourly averaged velocity, temperature and salinity data for each deployment are discussed below. The current velocity has been optimised in order to obtain a correct direction for the velocity by removing local topographical influences.

March 1991 - June 1991

The first deployment, between 7 March 1991 and 1 June 1991, Figures 3.91-3.93, indicates oscillations with periods ranging from one to 15 days approximately in all three properties. The speed varies between 10 cm/s to 50 cm/s, and approaches zero a few times, but a blockage is not observed in this deployment, which did cover the months during which blockages of the lower layer flow are more probable. The zero velocity near the end of the period is due to fouling of the rotor.

June 1991 – August 1991

Almost no velocity data were obtained, due to frequent fouling of the rotor. The temperature and salinity, Figures 3.94-3.95, indicate several periods of oscillation.

August 1991 - October 1991

Most of the velocity data were lost due to fouling, Figure 3.96. For the period for which the velocity data were obtained, the average velocity is seen to be about 25 cm/s, and the fluctuations are smaller. The salinity and temperature records, Figures 3.97-3.98, indicate a decrease in both properties at about 10 days after deployment, which indicates mixing of the cold intermediate layer from the Black Sea into the bottom layer.

December 1991 - August 1992

A continuous and long time series of data were obtained during this deployment. The velocity, temperature and salinity data for the full deployment period are shown in Figures 3.99-101. The blocking of the lower layer is seen on the velocity record as zero or negative speeds, the latter indicating inflow of the Black Sea water at the bottom of the Bosphorus. In the temperature and salinity transects, blocking events are characterised by low values. In some cases, the temperature and salinity of the Black sea water were out of range of the sensors of the current meter; these data appear as straight lines in the Figures. It is seen that the blockages occur during December and May.

A frequency analysis of the velocity for this record was done to determine the frequency of blocking. Using velocity intervals of 10 cm/s, the distribution of the velocities is as follows:

Velocity range	% frequency
0 – 10	11.5
10 – 20	19.0
20 – 30	32.2
30 – 40	23.5
40 – 50	9.4
0 – -10	1.7
-10 – -20	0.7
-20 – -30	0.7
-30 – -40	0.6
-40 – -50	0.7

From this distribution, it is seen that the occurence of blockage is less than 5 %.

Low passed velocity data for each month of this deployment are shown in Figures 3.102-109 to indicate the variabilty in the velocity and the oscillatory character of the flow. The low pass filter results in smoothing of the peaks, so that the maximum velocities are lower in these Figures than in Figure 3.99. The continuous and often large fluctuations in the velocity imply a continually changing lower layer flux, and confirm the variability observed in the ADCP flux measurements.

August 1992 - September 1993

In this deployment, again two current meters were installed; however, both rotors were fouled soon after the deployment. The little amount of velocity data obtained are not believed to be reliable and are not presented. However, the temperature and salinity data were recorded continously. The temperature sensor had a range of 0.3°C to 32°C, thus the temperature and salinity data are correct within the accuracy of the instrument.

The temperature and salinity data are given in Figures 3.110-3.111. It is seen that the lower layer was blocked several times during the winter months. The dates of the blockages are as follows:

November 25 - 27, 1992
December 18 - 24, 1992
December 27, 1992 - January 3, 1993
January 25 - 27, 1993
February 2 - 8, 1993.

A frequency analysis of the lower salinity values ($S < 25$ ppt) which occur during blocking gave a value of 7 %, which is close to that found in the previous deployment for the velocity. Thus, it appears that the lower layer can be expected to be blocked less than 10 % of the time during the year, and that the blockages will occur essentially during December and May.

Kızkulesi sea surface measurements

The temperature and salinity variations in the surface layer of the Bosphorus were monitored using Aanderaa current meters at Kızkulesi. The current meter was suspended in the upper layer to a depth of about 1 m in a small cage which was tied to the strucure of the lighthouse. Due to the rapid fouling of the rotor in the surface waters and the proximity of the current meter to the structure, currents were not measured.

The temperature and salinity records for the period December 1991 - May 1992 are shown in Figures 3.112-3.113. The peaks in salinity correspond to the 'Orkoz' events, during which strong southwesterly winds cause a high degree of mixing of the lower layer into the suface waters, with a resultant short term peak in the salinity at the surface. Five

such events occured during the observation period. The temperature and salinity data for approximately the same period in the following year are shown in Figures 3.114-3.115. Two major Orkoz events can be seen in this period, and about five smaller ones. It is worthwhile keeping in mind that high surface salinities do not necessarily require the occurence of a strong southerly wind. The ADCP cruise of December 1993 was a case in which salinities of about 25 ppt prevailed at the surface, without any wind at all.

3.3 Sea Level Measurements

Sea level measurements were commenced towards the end of September 1993. An Aanderaa WLR7 water recorder was installed at Anadolu Kavağı at the northern end of the Bosphorus, and another at Fener Bahce in the Sea of Marmara near the southern exit of the strait. The hourly averaged sea level difference (Anadolu Kavağı minus Fener Bahce) for September 1993 - January 1994 is plotted in Figure 3.116, and that for March - April 1994 in Figure 3.117. Sea level data between 1 January and 20 March 1994 were lost.

The variation in the sea level difference ranges from a minimum of -20 cm on 28 December 1993 to a maximum of 73 cm on 30 January 1994, giving a range of 93 cm during the observation period. The average sea level difference is 26.5 cm.

Both Figures display oscillations with a wide range of periods. Spectral analysis of the sea level difference indicates a major peak at a period of 12 hours, Figure 3.118. This peak is related to the diurnal oscillations of the barometric pressure, as indicated by the similarity between the sea level difference spectra and the barometric pressure spectra for Florya, Figure 3.119. Sea level and barometric pressure spectra for other months are similar to these.

As seen in the discussion of the fluxes in Sec.3.1, the changes in sea level have an almost immediate effect on the flows in the strait. Results from two cruises of Bilim in the Bosphorus during October 1993 further illustrate this fact. Figure 3.120 shows the ADCP ensemble locations and Figure 3.121 the velocity profiles at these locations. To save space, only the first twenty ensembles are shown. The sea level difference was about -10 cm (southern end of the strait higher) at the time. As seen in Figure 3.121 the upper layer is blocked, and a northerly flow with a speed of about 100 cm/s prevails in the strait. The second survey was carried out on October 28, when the sea level difference was about 50 cm. The ensemble locations for this survey are shown in Figure 3.122 and the velocity profiles in Figure 3.123. It is seen that the flow is to the south and the lower layer can be distinguished only at the southern end of the strait. It is worth mentioning that the wind in both surveys was from the north east with a speed of 3 - 5 m/s.

The close relation between the velocities and the sea level difference, and the unsteady nature of the sea level difference imply an unsteady flow situation in the strait. The

dominant period in the spectra, 12 hr, is about the same as the time taken to complete a survey when meauring fluxes in the strait. Thus the fluxes at sections measured several hours apart may in fact be due to quite different flow situations.

3.4 Conclusions

The large number of measurents of the flows in the Bosphorus under various conditions have shown that the flows in the strait are in a continous state of adjustment in response to the changing sea level elevations at the ends of the strait. The bottom velocity from the moored current meter at Anadolu Kavağı displays large variations within a period of several hours. The major period of the oscillation is 12 hours. The sea level changes are in turn closely related to the fluctuations in the barometric pressure fluctuations.

CHAPTER 4

ACOUSTICAL BACKSCATTER MEASUREMENTS

4.1 Introduction

The wastewater discharged from the Ahırkapı diffusers forms a buoyant plume in an environment of two-layer Bosphorus stratification and currents. Because the wastewater contains particulate material and has a different density from the environment, acoustical backscatter from the plume can be detected with relatively high signal strength.

The wastewater is essentially land-derived wastes in freshwater. Therefore it is typically warmer and less saline than the ambient waters of the Bosphorus. The Mediterranean water in the Bosphorus lower layer near the discharge outfall has constant temperature and salinity of ~14.5°C and ~38.5 respectively, while the upper layer Black Sea waters have salinity of ~ 20 and temperature which varies with depth and the time of the year.

The behaviour of the wastewater plume in the Bosphorus environment is quite complicated as a result of the two-layer stratification, the rapid currents flowing in opposite directions in each layer, their transverse variations, and the turbulence and entrainment processes in the ambient waters. The wastewater is injected from 22 diffuser ports on each of the two pipelines located in a depth range of 40 - 60 m. The presence of the waters of the Golden Horn (the Haliç) as a subsidiary of the Bosphorus channel, and the bottom topography of the deep channel at the diffuser site and the southern Bosphorus sill are factors causing additional complications. The numerous plumes from the multiple ports combine to yield a line source of plume-like behaviour in the far-field. The plume typically rises due to its buoyancy in the lower layer, and becomes arrested at the interface between the upper and lower layers of the Bosphorus, but the swift undercurrents bend the plume to align it with the interface along the Bosphorus.

Because of the complex dynamical regimes of the two layer system, in-situ measurements during variable oceanographic conditions indicate different types of behaviour of the wastewater plume. The sampling problem contributes to the difficulties of plume observations. Although the plume has three dimensional structure, the ship observations can only be made along transects cutting through this structure. Furthermore, the pumping conditions (the number of pumps and pipelines operating) at a particular time also influence the observed plume properties.

4.2 Methodology

The İSKİ Ahırkapı sewage outflow plume in the vicinity of the diffusers was detected with the 30 KHz transducer of the JMC echosounder and the 150 KHz ADCP transducer on board the R/V BİLİM. Acoustic signal emitted from the transducers are scattered by suspended matter in the water column. Because the wastewater contains particulate material and has a different density from the environment, acoustical backscatter from the plume can be detected with relatively high signal strength.

The 150 KHz vessel mounted acoustic Doppler current profiler on board the R/V BİLİM is an accurate instrument that can be used to measure backscatter from underwater sources. The ADCP measures the intensity of the scattered signal (echo intensity) from suspended particulates relative to the emitted signal, and thus allows the calculation of the absolute backscatter in the water column.

During the backscatter measurements, the ADCP was set up to sample at a maximum of 100 bins at 1 m depth intervals, 2 m blank after transmit, and a 10 s averaging intervals.

Obtaining the backscatter from the echo intensity data requires careful calibration, used to eliminate thermal noise arising from the temperature variations in the ADCP electronics and the transducer. The calibration procedure described by the manufacturer was utilized. To calculate the backscatter signal strength from ADCP's Echo Intensity values, the following procedure was followed:

1) The noise level of the Echo Intensity counts is defined by applying calibration to the ADCP records. This calibration was done to determine the noise in the ADCP Echo Intensity records, which could result from the vessel's engine, the stability of power supplied to instrument, *etc.*

2) The noise counts were subtracted from all other echo intensity counts in the water column for each profile.

3) Due to the variations in the sound velocity in the water column, sound velocity data obtained from CTD profiling are used to account for the range-dependent attenuation and geometric spreading of the acoustic beams.

4) The corrected echo intensity counts were converted to backscatter power (dB) using the procedure given by the manufactrer.

4.3 Plume Observations

Acoustic backscatter in the diffuser region was measured during a number of different surveys corresponding to the different dynamical regimes of the Bosphorus. The best

measurements with clear separation from background noise were obtained during 18 May 1992 and 4 March 1993. During these dates the İSKİ pretreatment plant was instructed to pump wastewater at a maximum rate possible for the current operating conditions, and therefore three pumps were operating during the time of measurements, with a total discharge of $Q = 7.5m^3s^{-1}$. Due to the high levels of particulate material in the discharge, a well defined plume structure could be observed during the surveys. On the other hand, there were plenty of measurements from the other dates, but the sewage outflow plume was very weak during the normal operating conditions (one pump) hence plume structure could not be detected by ADCP measurements.

The general layout of the diffuser in the Ahırkapı region, showing its depth profile and plan view are indicated in Figure 4.1. The backscatter measurements were done across this diffuser starting from souther part of it and the transects continue till the plume was disappeared on the JMC echo sounder records. The ship tracks along three separate measurements during May 1992 and the position of the pipeline are presented in Figure 4.2. The ship track during the March 1993 case was similar.

4.3.1 Plume Acoustic Backscatter during 18 May 1992

Prior to the plume measurements, the currents regime and hydrography of the Bosphorus were investigated by ADCP and CTD measurements along the strait. Vertical profiles of the velocity vector at stations along the Bosphorus are presented in Figure 4.3. High velocities reaching 100 cm/s are indicated in the upper layer, while the currents in the lower layer were smaller, with an average of 20 cm/s.

In order to present the acoustical backscatter strength of the Ahirkapi sewage outflow plume, three separate transects (H1 - H3, Figure 4.2) were made across the diffuser pipeline starting from the south of the diffuser, repeated each time at different distances from the shore. Contour plots of absolute acoustic backscatter, and the corresponding echo sounder records along the same transects are presented in Figures 4.4 – 4.6 respectively for each case. Acoustical backscatter signal strength is plotted in dB units.

Along the deepest section (Figure 4.4), roughly along the tip of the diffuser pipeline (located in a bottom trough), the plume rise was limited to about 20 m above the bottom and it did not reach the pycnocline. The lower layer currents bent the plume northward, forcing it to move parallel to the bottom. Rapid decrease is seen in the plume backscatter in a distance of $\sim$500 m. The echosounder record (Figure 4.4b) indicated the main part of the plume body to be bent parallel to the ground, though there were some particles rising steadily towards the interface.

In contrast to the observations in the deepest part of the discharge, the transect along the mid-depth region (Figure 4.5a,b) showed that the plume rose continuously and became

arrested at the pycnocline level by forming a mushroom like structure. The plume occurs in the form of a concentrated patch of turbid water roughly 150 m wide, 30 m long and slightly inclined to the north. This three dimensional structure of the plume was probably associated with the locations of diffuser ports and the weaker lower layer currents closer to the shore in this part.

Along the shallow nearshore transect (Figure 4.6a,b), the plume was in touch with the pycnocline. Although a continuous region of backscatter appears to connect the plume into the upper layer, it is not clear that all of this backscatter is due to wastewater coming from the diffusers.

Firstly, a layer of increased backscatter within the upper layer in a depth range of 10 - 20 m is evident in the above figures. This maximum could be associated with the particulates transported in the upper layer, and the texture in the image of this layer in the echosounder records is reminiscent of billows associated with interfacial mixing processes. Secondly, the backscatter from this layer occurs both upstream and downstream of the plume, suggesting that these scatterers could have originated from a source other than the wastewater plume.

However, the uncertainties in these results do not exclude entrainment of the plume into the upper layer. The entrainment of the lower layer waters into the upper layer is a well-known process, and the largest relative contribution to entrainment occurs in the waters of the southern Bosphorus, due to dissipative hydraulics in the same region (Özsoy *et al.*, 1986).

4.3.2 Plume Acoustic Backscatter during 4 March 1993

During the cruise in 4 March 1993, it was observed that the flow of Black Sea water was blocked during a short period (Chapter 3). Therefore the sewage outflow during backscatter measurements corresponded to one of the rather rare conditions of the Bosphorus two layer current system. This extreme regime was observed only during the 4 March 1993 and in the following days the system recovered to normal conditions, and later, the lower layer was blocked during the dye experiment (Chapter 3).

The north-south and east-west components of the velocity along the transect starting from the south of the diffuser pipeline and continuing north are plotted in Figure 4.7. This transect approximately follows the same route as H1 in Figure 4.2. The southerly flowing part of the upper layer was confined to the upper 5 m of the water column and rest of the water column was flowing towards north. The northerly velocities were increasing with depth to reach a maximum of 70-80 cm/s near the bottom. The high degree of vertical mixing during conditions of blocking of the upper layer flow are evident in the vertical profiles of density at station B0 (Figure 4.8).

The echosounder and absolute backscatter measurements corresponding to Figure 4.7 are given in Figures 4.9a and 4.9b, respectively. In contrast to the May 1992 observations, a strong pycnocline could not be detected by the acoustic backscatter measurements, as confirmed by the CTD data. The plume rise was continuous, with slight bending due to the lower layer currents, but the echosounder records did not indicate whether the rise in fact reached the surface. It seems that the upper 10 m layer of low density water prevented the plume rise reaching to the surface, since a maximum in backscatter is observed at 10 m depth, slightly north of the diffuser, where the material from the diffuser may have reached.

4.4 Conclusions

The observations indicate that the outfall plume has different structure and dilution along various sections across the diffusers, implying the effects of bottom topography and horizontal variability on the Bosphorus current system and mixing processes. It is also noted that the level of variability observed only in a limited number of measurements is prohibitively large for assessments of wastewater mixing and dispersion based on acoustic imprints.

The above two experiments demonstrate that the dynamics of the Bosphorus current regime has significant influence on the mixing and dispersion of the Ahırkapı sewage outflow. In most cases, the plume rise is arrested by the existing stratification. Although the stratification in the southern Bosphorus is weakened by the dissipative vertical mixing mechanisms, it seems to be sufficiently strong to trap the effluents at depths below the upper layer.

Most rigorous mixing in the salinity structure and the highest plume rise was observed during conditions of blocking of the upper layer flow, in which case the sewage outflow plume can rise to reach depths very close to the surface. However, since the typical upper layer blocking cases last for a short time period (*e.g* one day), the effects of the effluent entrainment are limited on a long term basis.

It should be noted that all of the above measurements were carried out while the three pumps of the Yenikapı discharge station were operating. This was requested from İSKİ, to be able to test the most critical conditions. During the normal operating conditions using only one or two pumps, the plume rise was even more limited, and often did not reach the interface, as often shown by echosounder observations during our various cruises in the area.

CHAPTER 5

RHODAMINE-B DYE TRACING EXPERIMENTS

5.1 The İSKİ Wastewater Disposal System and the Ahırkapı Marine Outfall

The İSKİ Wastewater Disposal System was designed in the earlier decades (DAMOC 1971, Gunnerson and Özturgut, 1974, Gunnerson, 1974), around the idea of discharging the wastes into the Bosphorus undercurrent, considered as a viable option under the existing environmental constraints. Being a city of immense population and a large growth rate located in a critical area of the Turkish Straits System, the wastewater disposal option for the city of İstanbul was developed for the first time, without the benefit of a previously existing system. The system consists of various collectors and underwater diffuser discharges (Figure 5.1) which are partly built, and partly are being continued to be built. The Ahırkapı diffuser discharge is the currently operating system which discharges the wastewater collected at the Yenikapı pre-treatment plant directly into the lower layer flow of the Bosphorus at its sourthern end.

Dye tracing experiments were carried out to evaluate the performance of the waste disposal system and its effects in the marine environment. Dye injection was made at the Yenikapı pre-treatment plant (Figure 5.2), for the purpose of tracing its output along the Bosphorus to determine the dilution rates and the overall effects in the surface and bottom waters during normal and extreme conditions of flow.

5.2 Dye Tracing Experiment Design

The dye tracing experiment was designed to measure concentrations of Rhodamine-B dye as a marker for the waste discharges within the waters of the Bosphorus and the adjacent areas.

Since the dye experiment did not have a precedent in the area, and due to the fact that very few Rhodamine-B tracer experiments have been performed to date at a similar scale, and under conditions of swift currents such as in the Bosphorus, there was limited foresight to estimate the modes and quantities of dye injection, and to ensure the success of the measurement strategies with regard to detectability and sampling frequency. An example of a dye tracing experiment covering portion of a large estuary (northern Cheasapeake Bay) is described in Tyler (1984), in an environment of current velocities an order of

magnitude smaller than the Bosphorus. In the case of the Bosphorus, with current speeds on the order of 1 m/sec in either direction, it was realised at the outset that the direct measurement of tracers would require special techniques and arrangements to solve the logistics of sampling. It seemed necessary that more than one ship would have to be involved, and the fluorescence measurements be recorded continuously and with proper synchronization with the other measurements. This was made possible with the use of modern oceanographic instruments and accurate ship positioning obtained and recorded simultaneously with the measurements.

Even with the questions on logistics of sampling solved, inevitably, we would have to search for trace quantities of dye under unlikely conditions. Moreover, the magnitude - and the expense - of the operation would be such that all components would have to proceed smoothly once the experiment had started. It was therefore essential for the eventual success of the dye tracer experiment to expend considerable effort in ensuring that the properties of the tracer and of its mixture with the Ahırkapı waste were well understood under all circumstances.

Initially, two different dye release experiments were considered. One of the two sets of measurements was designed to be made following an instantaneous release, and the other during a continuous release. The advantage of an instantaneous release is the smaller amount of dye required, though it is more difficult to follow the dye patch. On the other hand, a continuous release is easier to follow, but it requires large amount of dye. For a first time, we decided to carry out both types of experiments in August - September 1992.

Based on the results of the first experiment, two other experiments were performed during March 1993 and December 1993, during which only instantaneous releases were made. These two experiments were designed to capture the features of dye dispersion during extreme events of upper and lower layer blocking in the Bosphorus, as described in Chapter 2. The occurrence of these events are of a transient nature, and often can not be predicted, although there is only a seasonal expectation of occurrence based on the seasonal variation of the net fluxes and of the favorable wind conditions. We therefore waited for these conditions to occur based on our experience gained from earlier measurement programs. On the other hand, even when expectations are high, it is usually a difficult problem of logistics to organize a dye tracing experiment at the correct moment. However, our experience, supported by analyses of daily weather maps *etc.*, did not fail us, and we were able to make dye release experiments during the extreme events. The conditions for lower layer blocking developed during March 1993, but these conditions changed rapidly during the experiment. In the experiment of December 1993, the upper layer flow of the Bosphorus was blocked; in fact this was the most extreme transient event that we observed to date, with the upper layer waters of Black Sea origin temporarily pushed back as far as the northern entrance of the Bosphorus, but rapidly recovered in the next day as the front advanced south towards the constriction area in the southern Bosphorus.

The main objectives of dye tracing experiments were to determine the maximum level of contaimanants reached in the surface layers, and to quantify the respective amounts transported to the Marmara and the Black Sea as a result of waste discharges from the diffuser source located near the southern end of the Bosphorus in the lower layer of the exchange flows. The Rhodamine dye simulated the spread of wastewater since it was in solution with it. The bulk of the dye mass was expected to move towards the Black Sea with the lower layer. On the other hand, any dye that becomes entrained into the upper layer would move towards the Marmara Sea. This required at least two platforms (ships) to follow the dye patches moving in opposite directions towards the adjacent seas. One of the ships was the R/V BİLİM of the Institute of Marine Sciences, Middle East Technical University. The other ship was the R/V ARAR of the Institute of Marine Sciences and Geography, İstanbul University.

The two oceanographic ships were equipped with CTD systems (Seabird 911 Plus) with on-board fluorometers (Chelsea Instruments Aquatracka III) interfaced to these systems. The R/V BİLİM had also a light transmissometer for measuring suspended particulates during the first experiment, also on board the CTD, and a rosette system coupled to it to collect water samples. On the R/V BİLİM the vessel-mounted acoustic Doppler current profiler (ADCP) was also used for the collection of current data.

A third platform, the 'MURAT REİS', which was actually a small boat hired for the study, had another fluorometry system (Navitronics) powered by a generator, and was charged with liaison duty between the moving dye patch and the ships:, *i.e.* it would travel ahead of R/V BİLİM to detect the presence or absence of dye at a particular section along the Bosphorus, or stay behind and measure the decay of dye at a particular point. It was used in both ways, and also for measuring dye in hard to reach areas such as the Golden Horn.

In the last experiment during December 1993, only one ship, the R/V BİLİM, was used for surveying the Bosphorus region, because we did not expect surface water effects in the Marmara Sea during upper layer blocked conditions.

The operation required careful planning, and calibration before the experiments. The specific operating conditions in the Bosphorus, (*i.e.* heavy ship traffic, fast currents, and maneouvering of the ship either to attempt to stay fixed at a station, with instruments lowered, or during transects across the Strait perpendicular to the traffic) required good communication between the scientific crew and the bridge, and skillful handling of the requests by the captain and the crew. Furthermore the severe sampling problem, i.e. the rapid travel time of the dye patch and its nonuniform distribution, required careful timing for the ship to move from one station to the next.

Because the transit time of the dye through the Bosphorus is relatively short (about one day), logistics in sampling was of critical importance. Assuming a lower layer current

speed of 0.3 - 1.0 m/s, we find the transit time of the centroid to be 0.5 - 1.5 *days*. The requirement to finish all of the detailed measurements during such a short time period, despite the various complications due to traffic and ship operations, required a special sampling strategy as follows:

At the initial moments of the dye release from the Ahırkapı diffusers, we attempted to take samples in the source region. Usually, when two ships were present, both ships occupied stations in the source region at the same time, taking repeated samples in the near field of the diffusers. Even with these many attempts, the sampling of the dye was intermittent because of the three-dimensional and irregular geometry of the dye plumes issuing from the multi-port diffusers in the source region. The total time we could allocate for such sampling was short because the length of time for the dye issuing from diffusers during instantaneous discharges was on the order of 10 - 30 *min*, and the ships had to move to the other sampling positions along the Bosphorus and Marmara to follow the dye clouds.

After sampling in the source region the R/V BİLİM moved to the Bosphorus where it occupied stations along the Strait, and the R/V ARAR moved to the Marmara Sea where it occupied stations in the exit region. There were three types of measurements in the Bosphorus:

At regular stations along the Bosphorus, the profiles of temperature, salinity, light transmission and fluorescence were obtained with the CTD/fluorometer system, and the current velocity profile was obtained with the shipboard ADCP system. For this type of measurements, many stations were occupied along the Strait, at every opportunity of sampling. The small boat equipped with a separate fluorometer guided the sampling, by issuing reports about the absence or presence of dye along the Bosphorus at different times.

There were other stations occupied as the ship drifted slowly across the Bosphorus, which were used for flux calculations. During such cross-sectional sampling, the ADCP profiler was run continuously to collect averaged velocity profile data at very short intervals of 30 - 60 s along the ship course, and the CTD profiler was lowered and raised at few (up to 4) stations across the channel. The current and CTD profiles were later matched in time and horizontal positioning, to integrate concentrations and normal velocity across the cross-section to calculate the fluxes of dye and water. It was essential to determine strategical locations for these cross-sections, *i.e.*, strong currents, regular channel bathymetry, relatively small areas of shallow depth on flanks, straight channel geometry, *etc.* Good examples of such cross-sections occur near Staions B5, B8, B14, B15, but traffic and operations limitations such as at the narrow B8 section can be constraining.

In addition to these, continuous monitoring was considered at some cross-sections, to be able to calculate the total dye flux along the Bosphorus, by integrating in time the repeated measurements of the dye flux. By adding the fluxes over time, the net amount

of dye passing through a particular station can be determined. Comparison of the integrated dye mass with the injected mass creates a possibility to judge the efficiency of the disposal system in transporting the wastes to the Black Sea. The strategy for this type of measurements was severly limited by physical facts: Firstly, the total time for the dye cloud to pass a particular location was on the order of several hours, and increased with the coefficient of longitudinal dispersion and with distance from the source. For example, the estimates for the approximate duration of dye passage (Section 5.6) was about 6 hr for station B5 (7.5 km downstream of the source), and 12 hr for station B15 (28 km) near the northern entrance. On the other hand, since the whole operation was limited by the total time available for the different measurements, we could not do total flux measurements at more than one section. It was decided that such measurements could feasibly be done at section B5 alone.

5.3 The Use of Rhodamine-B Dye as Tracer

Fluorescent dyes are frequently used as tracers in marine dispersion / diffusion studies because they are water soluble, relatively harmless and may be detected in sea water in extremely low concentrations by modern instruments. In recent years there have been many examples of the assaying of Rhodamine dye by dedicated *in situ* fluorometers for the purpose of quantifying dispersion coefficients, verifying models of turbulent diffusion and determining the mixing of marine waters.

According to the literature (*e.g.* Wilson,1968), the greatest advantage of using Rhodamine-B as a tracer dye is its high detectibility. On the other hand, its adsorption on solids is a disadvantage, and Rhodamine-B in acetic acid solution is of moderate adsorptive tendency. The water quality parameters which affect Rhodamine fluorescence are temperature, total suspended solids, chlorine, photochemical decay and pH.

We performed a limited amount of laboratory studies on the Rhodamine dyes before planning the tracing experiments. The fluorescence behaviour of the dye solutions was examined using a Hitachi F3000 spectrofluorometer. The experiments were performed on two samples of Rhodamine dye; pure Rhodamine-B which is poorly soluble in water, and Rhodamine-B, a technical dye supplied in a 40% solution in acetic acid. These results, together with the specification of the Ahırkapı discharge were used in planning the quantities of Rhodamine needed for tracer dye experiments.

The outstanding property of Rhodamine dye is its strong fluorescence, the wavelengths corresponding to maximum excitation and emission (uncorrected) being 554nm and 574nm respectively (Figure 5.3). These wavelengths are tolerably close to those at which flavins (500-550nm) and chlorophylls (600-660nm) fluoresce in sea water and, the dedicated in situ fluorometers supplied by Chelsea Instruments having a wide bandpass, emphasize the

need for careful background measurements to be available before the fluorescence of trace quantities of Rhodamine in sea water is assessed.

Laboratory experiments showed that neither sea water, samples of Ahırkapı waste water nor acetic acid changed the maximum excitation or emission wavelengths of Rhodamine dyes. The intensity of emission was affected - thus technical Rhodamine dissolved in acetic acid fluoresced approximately 50% more than similar solutions dissolved in water. However, when solutions were diluted with Mediterranean sea water to concentrations of *ppb* (or low *ppm*) levels, reproducible results were always obtained, the limit of detection being of the order of 0.01 *ppb* of Rhodamine.

At the *ppb* level, fluorescence by Rhodamine was directly proportional to its concentration but at higher concentrations the relationship was non-linear. Finally, when the concentration is increased beyond a saturation limit the sensitivity of the fluorescence measurement changes sign, and tends to zero at very high concentrations (Figure 5.4). This area of negative instrument sensitivity is beyond the typical range of measurements in the marine environment. However, the initial concentrations of dye during injection into the wastewater tanks are often within this range of nonlinear behaviour, and measurements can only be obtained by dilution of the samples.

The Rhodamine-B dye typically adheres on particulate material, especially at the high concentrations. In the present case of its injection into wastewater, it is therefore inherent that the dye is adsorbed onto the suspended load present in the wastewater.

The adsorption on solid surfaces of materials in solution can be represented by the Langmuir relationship:

$$\left(\frac{m_a}{m_s}\right) = \left(\frac{m_a}{m_s}\right)_{max} \frac{\alpha c}{1 + \alpha c},$$

or alternatively by the Freundlich relationship:

$$\left(\frac{m_a}{m_s}\right) = kc^{1/n},$$

where m_a is the mass of material adsorbed, m_s is the mass of solid on which adsorption takes place, c is the concentration of material in solution, and $A_o \equiv (m_a/m_s)_{max}$, α, k, and n ($n > 1$) are constants (Shaw, 1991).

We note that the first formulation leads to a saturation level $(m_a/m_s)_m ax$ when $c \to \infty$, wheras the second formulation leads to a monotonous increase of relative adsorption with increasing concentration.

If we consider that the concentration c_o of dye initially present in solution will be absorbed on solid particles in wastewater with a concentration of $c_s \equiv m_s/V$ (V is a fixed volume of the solution), there will be a loss of dye of concentration $c_\delta \equiv m_a/V$, yielding a residual dye concentration of c_1, *i.e.*:

$$c_o - c_\delta = c_1 .$$

Using the Langmuir type of formulation, and the above definitions, we obtain

$$c_\delta = A_o \frac{\alpha \; c_s \; c_o}{1 + \alpha c_o},$$

which indicates that the dye loss due to adsorption is proportional to the suspended solid concentration in the wastewater, as well as the dye concentration. It is also noted that the dependence on dye concentration vanishes at large c_o (saturation). In fact, the ratio of adsorbed dye to initial concentration (c_δ/c_o) is an inverse function of the dye concentration c_o.

The ratio of residual to initial dye concentration (the ratio of dye reduction due to adsorption) is then

$$\left(\frac{c_1}{c_o}\right) = \frac{1 + \alpha \; (c_o - A_o c_w)}{1 + \alpha c_o}.$$

The ratio $(c_1/c_o) < 1$ and approaches $\sim 1 - A_o \alpha c_w$ for large concentrations of suspended solids.

In contrast to the simple representations above, the actual adsorption process is expected to be much more complicated. The multiple species of solid material with different size distribution and surface features, and the chemical sorption effects (chemisorption) would certainly be important in the case of Rhodamine dye adsorption by İSKİ wastewater.

The adsorption of Rhodamine by the particles was studied in the laboratory. Only ~0.5% of pure Rhodamine-B was adsorbed by the wastes but technical Rhodamine, readily soluble in acetic acid, was strongly adsorbed, the fraction adsorbed - which could readily amount to 25% but which depends on the nature of the adsorbing solid - being directly proportional to the concentration of Rhodamine in solution. To minimise adsorption and loss of Rhodamine it is clearly necessary to use very dilute solutions at all times.

Laboratory experiments with İSKİ wastewater collected from the pretreatment plant showed a high percentage of loss due to adsorption by particulates (Figure 5.5). Computations based on the above measurements indicate a adsorbance reduction ratio of $(c_1/c_o) = 0.25 - 0.6$.

The above experiments were done with a few samples of the İSKİ wastewater. In reality, the adsorption factor is a function of the solids present in the wastewater, which is widely variable in the İSKİ discharge. For example, of the 215 measurements of total suspended solids (TSS) in different parts of the treatment plant in the period of January - December 1990, the mean was 225 mg/l with a standard deviation of 180 mg/l, and the measurements had a range of 3 - 1160 mg/l. Depending on the instantaneous conditions, the range of variability may be even higher, and this means that the adsorption of dye onto suspended solids would also change in a wide range depending on these conditions.

To test the influence of particulate concentration on the adsorbtion, we added 0.2 *ppb* of beaach sand to wastewater sample containing 200 *ppm* of Rhodamine-B. The concentration measured in the solution decreased with time. After 1 *hr* the dye concentration in the centrifuged sample reduced by a additional factor of 0.84, and after waiting about 15 *hr* it decreased by a a similar factor of 0.71. Taking these effects into consideration could further reduce the ratio of (c_1/c_o).

Note also that the concentration of total suspended solids in the wastewater is very high, *i.e.* in the *ppm* to *ppt* range. Similarly, the initial Rhodamine dye concentration during injection into the tank is also very high, in the 100 *ppm* levels (visibly red), and immediately reduces to *ppb* levels (see following sections) in the Bosphorus. Having inititially high concentrations of both the dye and the adsorbing material is a situation that could not be avoided during the injection period as a result of the detection limits required in the Bosphorus, which could be responsible for high ratios of dye loss at initial time, according to the above estimates.

Further to the above facts, additional adsorption occurs due to the contact of the dye with solid surfaces in the injection tank and along the discharge pipeline (of length 3.6 *km*) connecting the tank to the diffusers. It is not possible to quantify these effects. Considering all of the above possibilities, it would be reasonable to expect that the actual

ratio of dye reduction by adsorption would be less than 50 %. A reasonable range of reduction ratio would be $(c_1/c_o) = 0.1 - 0.5$, depending on the instantaneous conditions.

Additional experiments were done on the decay rate of Rhodamine-B with time. Under typical conditions of the Bosphorus lower layer, where very little light penetrates at all, the decay rate is expected to be very small, since the main reason for dye loss due to decay is its degradation by sunlight. Various experiments were done in dark bottles, and almost no sign of Rhodamine dye decay was found.

Although photochemical decay of the dye can be neglected, the adsorption process could continue after injection, and for reasons that will become clear in Sections 5.6 and 5.9, we will need to include some form of decay, not only to account for the chemical processes of decay, but also to represent the loss of dye from the lower layer into the upper layer. The decay of dye is characterized by the decay coefficient K_d, which can be related to the decay time scale, *e.g.* the half-life T_d of decay, as follows:

$$K_d = \frac{ln(2)}{T_d}.$$

5.4 In-situ Fluorometry and Instrument Calibrations

Two state-of-the-art instruments were used for *in situ* Rhodamine-B fluorescence measurements on board the R/V BİLİM and R/V ARAR. Both instruments were Chelsea Instruments Aquatracka III submersible fluorometers interfaced with Seabird 911 Plus CTD profiler systems. The data from the fluorometer is passed to the CTD system where it is digitized and included into the data stream of the profiler, which is then logged by special (Seabird) software on personal computers. This automated and high frequency sampling was required to collect fluorescence data simultaneously with CTD data (depth, temperature, salinity), in order to locate dye patches with accuracy and relative to the distribution of seawater physical properties.

The fluorometers were calibrated on board, with stock solutions of Rhodamine-B diluted to desired levels used for repeated measurements. Two independent calibrations were made for each instrument with standard solutions diluted with distilled water and sea water. In the operating range the dependence of fluorometer voltage to concentration is logarithmic. The voltages were therefore converted to calculated fluorescence c_c as follows:

$$c_c = \frac{10^{V_s} - 10^{V_b}}{10^{V_1} - 10^{V_b}}$$

where V_s is the measured voltage signal by the fluorometer for given concentration, V_b the background value of the fluorometer voltage measured with a blank (distilled water with no dye present), V_1 the fluorometer voltage for 1 *ppb* of concentration. The normalization with respect to 1 *ppb* allows calculation of dye concentration c_c directly in *ppb* units. Since the fluorescence for sea water and distilled water blanks did not differ greatly, the distilled water background was used in the calculations. Salinity dependent corrections to the actual measurements were made later, as described in Section 5.8.

The calibration curves showing measured concentration (with background values subtracted as indicated above) versus sample concentration are given in the following figures (Figures 5.6 - 5.8). Because a particular fluorometer was paired with a CTD in each cruise, and as a result of shifts in calibration with time, the instruments were re-calibrated at the beginning of each experiment. The serial numbers of the CTD and fluorometer systems, and the Figures for corresponding calibration curves are given in the following:

Date	Ship	CTD Serial Nr.	Fluorometer Serial Nr.	Calibration Curve
Aug.-Sep. 1992	BİLİM	95526-0242	88/725/024	Figure 5.6.a
Aug.-Sep. 1992	ARAR	95526-0243	88/725/023	Figure 5.6.b
March 1993	BİLİM	95526-0243	88/725/024	Figure 5.7.a
March 1993	ARAR	95526-0242	88/725/023	Figure 5.7.b
December 1994	BİLİM	95526-0243	88/725/023	Figure 5.8

In addition to the Chelsea Instruments fluorometers used on the main ships, a Navitronics fluorometer was used on board a small boat to monitor the dye patch along the Bosphorus and detect its arrival time at alternative locations. However, the performance of this instrument was not very good, and since it was only used for the above purpose, details of its calibration are not given.

5.5 Dye injection

The Rhodamine-B dye was introduced at the aerated grit removal tanks of the Yenikapı Pre-treatment Plant (Figure 5.2). These tanks constitute the last accessible area before the disharge is pumped through the pipeline leading to the Ahırkapı diffusers. There are two parallel pipelines each driven by three pumps. During normal operation, the pumps are operated according to demand, depending on the current level of wastewater in the discharge tanks. Each pump has a 700 *kw* power rating, supplying a nominal discharge capacity of 3 m^3/s. A number of pumps may be operated on either or both of the pipelines according to the required volume discharge.

During the dye release experiments, arrangements were made to obtain a steady pumping rate. For this purpose, only one of the pipelines was used, and a fixed number of pumps (one or two) were operated during the injection.

An overflow path exists, feeding wastewater to the pipelines by gravity when the pumps can not discharge sufficient volume. Under those conditions part of the wastewater can be discharged to the surface waters near the Yenikapı pre-treatment plant (*i.e.* into the Marmara). Care was taken to avoid such conditions, and did not occur during the injections, except during the case of the December 1993 experiment.

The Rhodamine-B dye was in the form of 30 l containers of 40 % solution in acetic acid. The dye was diluted to the desired concentration by adding it to an appropriate volume of water. A convenient table for conversion of frequently used concentration units and the instrument ranges are given in Appendix 1.

During the instantaneous release experiments, the pretreatment tank was completely blocked, the dye was introduced into it, and allowed to be thoroughly mixed by the existing aeration mechanism. The tankful of wastewater was then pumped out to the diffuser.

During the continuous pulse release, the necessary amount was first mixed with water in a small tank outside the pretreatment tank, and then continuously fed into the pretreatment tank at a reasonably steady rate.

5.5.1 Experiment of August - September 1992

The instantaneous dye release was made on 29 August, and the continuous pulse release was made on 1 September 1992. Only one pump on one of the pipelines was operated (at an approximate pumping rate of $2.0 m^3/s$), and the other pumps were blocked. Similarly, the pre-treatment tanks other than the one used for injecting the dye were blocked off. The pumping rate was estimated to be 2 m^3/s under the summer conditions. In either case, the dye patches were then followed for two days in the adjoining waters of the Bosphorus and Marmara.

The instantaneous injection was started at 11:00 a.m. on 29 August 1992. The dye measurements in the Bosphorus and the Marmara were made on 29 and 30 August, 1992.

450 l of 40 % solution (= 180 kg of pure Rhodamine-B) was used in the instantaneous release case. Since the tank has a volume of 900 m^3 filled by dye containing wastewater prior to injection, the average concentration is calculated to be 200 ppm, without accounting for adsorption.

Repeated measurements of Rhodamine-B fluorescence in the pretreatment tank before the release showed concentrations of 550, 420, 42, 38, 52, 500, and 94 ppm, respectively in

7 random samples, the average of which was 242 $\pm$ 236 ppm. This is comparable to the calculated average concentration, but the high variability of dye concentration in the samples measured makes this comparison suspect. Comparison of these measurements with the input concentration yields a reduction factor of $\simeq 1.2 \pm 1.2$ (*i.e.* a range of 0 - 2.4) due to adsorption. Since there are no better measurements of initial dye concentration, we assume that a dye reduction factor of 0.2 - 0.6 is appropriate for the adsorption effects, as discussed in Section 5.3. This puts a large uncertainty in the total amount of measurable dye reaching the sea, as will be shown in the following Sections. For practical purposes the dye reduction ratio due to adsorption can be taken as 0.5, but there is no real justification for this number.

The continuous injection started at 8:45 p.m. on 31 August 1992, and continued until 12:30 p.m the next day. The measurements were made on the dates of 1 and 2 September, 1992.

During the continuous pulse release, 60 l of 40 % solution (= 24 kg of pure Rhodamine-B) was mixed into the tank per hour, and the equivalent of 408 kg of pure Rhodamine-B was introduced during a total period of 17 hours. With a dye injection rate of $q_i = 24kg/h$, and a pumping rate of $Q = 2.m^3/s$, the initial concentration in the tank would be $c_i = q_i/Q = 3.33ppm$, without accounting for adsorbtion. If an adsorption ratio of 0.5 was assumed the tank concentration would reduce to $c_t = D_a c_i = 1.67ppm$. The few measurements concentrations made in the pretreatment tank were $\sim 5 \pm 0.4ppm$, based on three samples (far too few) during the discharge. This would imply a dye increase rather than a dye reduction due to adsorption; and therefore we do not rely on these measurements and take an adsorption ratio of $D_a = 0.5$ as in the previous case.

5.5.2 Experiment of March 1993

The instantaneous injection was started around 7:30 a.m. on 5 March 1993. The dye measurements in the Bosphorus and the Marmara were made duing 5 - 7 March 1993. Although the dye was pumped through a single pipeline, two pumps were operated (each working at the maximum pumping rate of $3.0m^3/s$).

780 l of 40 % solution (= 312 kg of pure Rhodamine-B) was used in the instantaneous release. The dye was diluted in two aeration tanks each having a volume of $600m^3$. The mean concentration in the tanks is calculated to be $\sim 260ppm$, not accounting for adsorption effects. Concentration measurements were obtained at five points along each of the two tanks before pumping. These measurements yielded 611, 317, 228, 58 and 28 ppm in the first tank, and 361, 357, 285, 122 and 65 ppm in the second tank respectively, indicating inhomogeneous distribution of the dye in the tanks. This yields an average concentration of $243 \pm 182ppm$ in the tanks. Comparison of these measurements with the input concentration yields a reduction factor of $\simeq 0.93 \pm 0.70$ due to adsorption.

5.5.3 Experiment of December 1993

The instantaneous injection was started around 7:30 a.m. on 18 December 1993. the dye measurements in the Bosphorus and the Marmara were made during 18 - 19 December 1993. One pump was used for discharging the dye through a single pipeline, as in the case of the August-September 1992 experiments.

780 l of 40 % solution (= 312 kg of pure Rhodamine-B) was used in the instantaneous release. The dye was diluted in one aeration tank with a volume of $900m^3$. The mean concentration in the tanks is calculated to be $\sim 345ppm$. Repeated concentration measurements in the tank before pumping yielded 83, 85, 76, 78 and 39 ppm respectively, yielding an average concentration of $72 \pm 19ppm$ obtained from the 5 samples. Comparison of these measurements with the input concentration yields a reduction factor of $\simeq 0.21 \pm 0.06$ due to adsorption.

During this experiment, some of the dye prepared in the aeration tank escaped by gravity overflow into the surface waters of the Sea of Marmara. The exact amount of the dye that escaped is not known.

5.6 Predictions and Sensitivity Runs Based on Simple Models

For planning of the dye injection and the dye tracing experiments, predictive calculations of the dye concentrations were made at the diffuser outlets and in the Bosphorus, based on simple models and a number of simplifying assumptions. The assumptions, parameter values used, and the estimated maximum concentrations and scales are provided in the following, so as to provide a sense of the relative importance of individual processes of dilution, and orders of magnitude of the expected dispersion effects.

5.6.1 Adsorption, Pipeline Dispersion and Diffuser Dilution Calculations

5.6.1.1 Methods of Calculation

If V_t is the volume of outlet tank, and M_i is the mass of dye injected, the initial concentration c_i in tank is $c_i = M_i/V_t$. By adsorption, this initial concentration is reduced by a factor D_a, as discussed in Sections 5.3. For practical purposes we could assume a range of $D_a = 0.1 - 0.5$ for the İSKİ waste. Although adsorption possibly occurs on tank and pipeline surfaces, in addition to that bound on suspended solids, we assume all of it occurs in the tank before pumping occurs. Then the dye concentration in the tank is estimated to be $c_t = D_a\ c_i$.

The pipeline dispersion depends on the geometry and the pipeline discharges. In general, there are two pipelines, with discharges of Q_1 and Q_2, giving a total discharge of $Q =$

$Q_1 + Q_2$. A maximum of two pumps can operate on each pipeline, and each pump can discharge a maximum of 3.0 m^3/s. The radii of the two pipelines from the Yenikapı pre-treatment plant to the diffuser structure are nominally $r = 1\ m$, and their lengths are $l = 3600\ m$.

The mean velocity in the pipeline is $\bar{u} \equiv Q/(\pi r^2)$, and the transit time through the pipeline is $T_p = l/\bar{u}$. The calculated transit time was taken into account for correct time referencing of the dye patches in the Bosphorus relative to the time of exit from the diffuser.

For pipeline dispersion calculations we assume pipe roughness parameter of $k_s = 0.5\ mm$ ($k_s/r = 0.0005$), kinematic viscosity of $\nu = 10^{-6}\ m^2/s$. Assuming that the flow is in the 'completely rough' regime ($u_* k_s/\nu > 70$), the pipe resistance coefficient can be calculated from the von Karman equation (Schlichting, 1979, p. 584), which yields $\lambda \equiv [2log_{10}(r/k_s + 1.74)]^{-2} = 0.023$. The friction velocity in the pipeline is $u_* \equiv \bar{u}(\lambda/8)^{1/2}$, and the pipe dispersion coefficient is then calculated from the well known Taylor shear flow dispersion formula (Fischer *et al.*, 1979, Table 5.1, p.93), $E_p \equiv 10.1 u_* r$.

When the dye present in the tank enters the pipeline it takes the form of a plug of length $l_p = V_t/(\pi r^2)$ with concentration same as in the tank, $c_t = D_a c_i$. The duration of injection of the plug is $t_p = l_p/\bar{u}$. Consequently, the situation is the same as continuously injecting the dye at rate $q_p = c_t V_t/t_p = \bar{u}(\pi r^2)c_t$ during a pulse duration of t_p in a uniform one-dimensional flow.

As a result of pipe dispersion, one would expect dye spread to occur at the diffuser outlets. If one would assume that the initial source was instantaneous, one standard deviation of this spread after traveling through the pipeline would be $\sigma_x = (2E_p T_p)^{1/2}$, and the corresponding spread in time would be $\sigma_t = \sigma_x/\bar{u}$.

Accordingly, the dilution due to the sum of the adsorption, pipeline dispersion and diffuser mixing can be calculated from one-dimensional solutions of dispersion equations for a continuous source of limited duration (*e.g.* Özsoy, E. and Ü. Ünlüata, 1988). The solutions for concentration at the source region of the Bosphorus, after exiting from the diffusers can be written as follows:

For $0 < t < t_p$,

$$c_p(t) = D_a D_d c_i \frac{1}{2}\{e^{-\frac{K_d x}{\bar{u}}}[2 - erfc(\frac{\bar{u}t - x}{\sqrt{4E_p t}})] - e^{\frac{x\bar{u}}{E_p}} erfc(\frac{\bar{u}t + x}{\sqrt{4E_p t}})\},$$

and for $t > t_p$,

$$c_p(t) = D_a D_d c_i \frac{1}{2}\{e^{-\frac{K_d x}{\bar{u}}}[erfc(\frac{\bar{u}(t-t_p)-x}{\sqrt{4E_p(t-t_p)}}) - erfc(\frac{\bar{u}t-x}{\sqrt{4E_p t}})]$$
$$+ e^{\frac{x\bar{u}}{E_p}}[erfc(\frac{\bar{u}(t-t_p)+x}{\sqrt{4E_p(t-t_p)}}) - erfc(\frac{\bar{u}t+x}{\sqrt{4E_p t}})]\}.$$

The time dependent dye concentration after the diffuser mixing, at the source region of the Bosphorus according to the above have been calculated with parameters corresponding to the experimental setting in each case.

The pipe dispersion calculations for specific cases below show that pipe dispersion is not significant, so that we can calculate the concentration at the diffuser exits by simply multiplying the tank concentration with appropriate dilution and adsorption factors $c_d = D_a D_d c_i$. The initial Bosphorus concentration distributed across the lower layer cross-section (needed in Section 5.8) is calculated as $c_o = c_t Q/Q_\ell$, where Q is the pipeline discharge, and $Q_\ell = baru_\ell A_\ell$ is the discharge for the lower layer of the Bosphorus.

5.6.1.2 August - September 1992

The maximum volume of the outlet tank $V_t = 900\ m^3$ was filled during this experiment. The dye mass was $M_i = 180\ kg$ as noted in Section 5.5. Only one pump discharged $Q = Q_1 = 2.0\ m^3/s$, so that the mean velocity in the pipeline was $\bar{u} = 0.6\ m/s$, and the transit time through the pipeline was $T_p = 5655\ s\ \simeq 1.5hr$.

Estimating a friction velocity of $u_* = 0.03\ m/s$, the pipe dispersion coefficient is calculated to be $E_p = 0.34\ m^2/s$, which yields $\sigma_x = 62\ m$, and $\sigma_t = 98\ s$. Note that these estimates of spread are small relative to either the length l_p or the duration t_p of the dye pulse injected to the pipeline. The calculated dye concentration after accounting for adsorptive reduction of $D_a = 0.5$ (Section 5.5), pipeline dispersion (dilution $\simeq 1$) and a diffuser dilution of $D_d = 0.02$, is shown in Figure 5.9. The maximum concentration was $c_d = 1.96\ ppm$, and the total duration of dye discharge was on the order of 15 - 20 min.

The above calculations show that pipe dispersion is not significant.

5.6.1.3 March 1993

The corresponding values of pipeline mean velocity and duration in March 1993 were $\bar{u} = 1.9\ m/s$, and $T_p = 1885\ s\ \simeq 0.5hr$. Because the pipeline dispersion does not contribute to dilution (dilution $\simeq 1$) the output concentration variations are not significant. However allowing for an adsorptive reduction of $D_a = 0.25$ (Section 5.5), and a diffuser dilution

of $D_d = 0.02$, the maximum concentration expected after the diffusers is expected to be $c_d = 1.3ppm$.

5.6.1.4 December 1993

The discharge conditions were similar to August 1992. Allowing for an adsorptive reduction of $D_a = 0.25$ (Section 5.5), and a diffuser dilution of $D_d = 0.02$, the maximum concentration after the diffusers is expected to be $c_d = 1.7ppm$.

5.6.2 Estimates of Mixing Time Scales and Dispersion in the Bosphorus

Based on semi-empirical results of the theory of mixing, the dispersion characteristics and time scales for the Bosphorus lower layer flow can be estimated. The mean geometrical characteristics, *i.e.* mean cross-sectional area and shape, volume flux, mean velocity, and bottom friction in the Bosphorus have to be given for these calculations. The geometrical and flow characteristics of the lower layer flow of the Bosphorus change as a function of distance and time, as indicated in Chapter 2. On the other hand, since we will give order of magnitude estimates, we make some assumptions regarding the average geometry and the flow characteristics.

For the purpose of the present estimates, we can assume that the Bosphorus cross-section is triangular in form, and that the dye is trapped in the lower layer flow without any loss to the upper layer. We assume fixed vaues of the maximum depth in the lower layer (h_ℓ) and the maximum width (w_ℓ), although these are in fact variable along the Bosphorus, as a function of Strait geometry and interface elevation above the bottom. Accordingly, the mean depth is $\bar{h} = h_\ell/2$, and the mean width is $\bar{w} = w_\ell/2$, and the cross-sectional area is $A_\ell = w_\ell h_\ell/2$. We define the mean half-width as $\bar{w}_h = \bar{w}/2$, and the hydraulic radius as $R \equiv w_\ell(2(1. + (w_\ell/(2h_\ell))^2)^{-1/2})/2$. The Darcy-Weisbach channel friction factor is calculated from $f \equiv 116n^2/R^{1/3}$, where n is called 'Manning's n'. $\kappa = 0.4$ is von Karman constant. L_b is the total length of the channel.

With $\bar{u}_\ell$ representing the lower layer current speed, the lower layer volume flux is $Q_\ell = \bar{u}_\ell A_\ell$, and the friction velocity is defined as $u_* \equiv \bar{u}_\ell(f/8)^{1/2}$.

Estimates of characteristic Bosphorus mixing times and dispersion coefficients can be made in the three principal directions (*i.e.* the vertical, transverse and longitudinal directions), following (Fischer *et al.*, 1979, equations 5.3, 5.4 and 5.19, pp. 106, 107 and 136; and Smith, 1986, equations 1.2, 3.5, 4.2, 4.5 and 5.12):

The vertical mixing coefficient and mixing time scale are estimated as

$$E_z \equiv 0.067\bar{h}u_*, T_z \equiv \frac{\bar{h}}{2\kappa u_*},$$

the transverse mixing coefficient and mixing time scale are estimated as

$$E_y \equiv 0.15\bar{h}u_*, T_y \equiv 16\frac{\bar{w}^2}{\bar{h}\bar{u}_\ell},$$

and the longitudinal mixing coefficient and mixing time scale are estimated as

$$E_x \equiv 0.04\frac{\bar{u}_\ell \bar{w}_h^2}{\bar{h}u_*}, T_x \equiv \frac{L_b^2}{E_x}.$$

The total length of Bosporus is $L_b = 30\ km$, the lower layer depth and width are $h_\ell = 30\ m$, $w_\ell = 500\ m$, yielding $A_\ell = 7500\ m^2$ and $Q_\ell = 3750\ m^3/s$, if we assume the average current speed to be $\bar{u}_\ell = 0.5\ m/s$. With a hydraulic radius calculated as $R = 14.9m$, and a Darcy-Weisbach friction factor of $f = 0.118$ (Manning's $n = 0.05$), the friction velocity is found to be $u_* = 0.061m/s$.

With these estimated values of the parameters, we calculate:

$$\begin{aligned} E_z &= 0.06\ m^2/s, T_z = 5.2\ min, \\ E_y &= 0.14\ m^2/s, T_y = 9.3\ hr, \\ E_x &= 171.6\ m^2/s, T_x = 60.7\ day. \end{aligned}$$

The longitudinal mixing coefficient is comparable to other estuarine regions of the world (Fischer *et al.*, 1979). It is recognised that the longitudinal mixing time scale of about 60 *days* is determined from dispersion effects alone, although in reality the dye patch would leave the Bosphorus shortly after the advection time scale $L_b/\bar{u}_\ell \simeq 17\ h$.

The vertical and transverse mixing time scales are much shorter (5 *min* and 9 *h* respectively). The estimates indicate that complete vertical mixing (within the lower layer) would occur promptly after the diffuser.

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We note that the above estimates for vertical mixing could represent a considerable simplification of the typical Bosphorus conditions, because they do not take into account the buoyancy of the wastewater and the ambient stratification near the pycnocline. In reality, the spreading of wastewater from the diffusers occur in the form of a buoyant plume, which would have a tendency to be trapped near the pycnocline, leading to much longer time scales of vertical mixing.

On the other hand, perfect transverse mixing is not expected to occur before the dye patch exits the Bosphorus into the Black Sea. In fact, the distance for transverse mixing is found to be comparable to, or greater than, the length of the Bosphorus Strait, if we calculate it from two different estimates corresponding to different locations of the source relative to the channel (Fischer *et al.*, 1979, equations 5.10, 5.10a):

The distance required for complete transverse mixing from a centerline source is

$$L_c \equiv 0.4 \frac{\bar{u}_\ell \bar{w}_h^2}{E_y} = 22.9 \ km,$$

and the same distance for a side source is calculated to be

$$L_s \equiv 1.6 \frac{\bar{u}_\ell \bar{w}_h^2}{E_y} = 91.5 \ km.$$

5.6.3 Concentration Variations and Maximum Levels in the Bosphorus

Bosphorus concentrations after instantaneous and continuous pulse releases are computed in the following, in order to have order of magnitude estimates, and to study the transport through the Strait.

We study the dispersion of dye released in the lower layer of the Bosphorus with a one dimensional model of the the average dye concentration in the lower layer, and neglecting the exchange of dye between the layers.

The exchange across the interface of uniformly distributed tracers (such as salinity) within each layer is known to be small, because of the two layer stratification of the Bosphorus. For example, about 25 % of the lower layer flow is estimated to be entrained into the upper layer, and about 10 % of the upper layer waters into the lower layer, based on steady state salt budgets (Section 2.2). Of these exchanges between the layers, the major part occurs

in the rather special mixing regions, *e.g.* in the hydraulic jump / internal mixing region near the southern end of the Bosphorus. In summary, for all practical purposes, we could assume the dye patch to be confined in the lower layer, or if there is a loss to the upper layer, we assume we could parameterize this loss with a decay term in the longitudinal dispersion equations, of which the characteristic constant is K_d, as introduced in Section 5.3.

With such a simple model we describe solutions of the one-dimensional diffusion equation

$$\frac{\partial c}{\partial t} + u_\ell \frac{\partial c}{\partial x} = E_x \frac{\partial^2 c}{\partial x^2} - K_d c.$$

A similar two-layer model of dispersion was studied by Thacker (1976), in which exchanges between layers were accounted for by a decay term in the one dimensional diffusion equations for each layer, including an additional equation for the upper layer concentration, coupled to the above equation. In the present case we assume that the lower layer concentrations are much higher than those in the upper layer, so that the entrainment into the upper layer is represented by the loss of dye into the upper layer (which is assumed not to return to the lower layer thereafter), reducing the system essentially to a single layer.

One of the findings of Thacker (1976), which is of direct relevance in the present case was the following: If the time is shorter than the decay time scale (*i.e.*, for small K_d), the solutions to the system of two-layer coupled equations produce differential advection of the dye in each layer, rather than a combined pattern of diffusion resulting from two-layer shear flow dispersion. The shear flow dispersion by the counterflowing currents only becomes important if enough time is given for vertical mixing to occur between layers. Therefore, we believe the above simple model could be used within the time period before the dye exits the Bosphorus into the Black Sea.

In addition, we assume pipeline dispersion to be negligible, and apply the dye injected in the tank to the source region of the Bosphorus, with a correction factor of D_a for adsorption. While the solution is not valid near the source region, it approaches the correct solution of one-dimensional dispersion within a short distance away from the diffusers, provided that complete vertical and transverse mixing are assumed.

For an instantaneous release of dye with mass $D_a M_i$ at $x = 0$, $t = 0$, the solution of the above one-dimensional diffusion equation is

$$c(t) = \frac{D_a M_i}{A_\ell \sqrt{4\pi E_x t}} e^{\frac{-(x-ut)^2}{4E_x t - K_d t}}.$$

The dilution of the dye at the northern end of the Bosphorus (the maximum concentration), relative to the tank concentration $c_t = D_a M_i / V_t$ is

$$c(L_b, t)_{max}/c_t = \frac{V_t}{A_\ell \sqrt{4\pi E_x (L_b/\bar{u}_\ell)}} e^{-K_d t}$$

.

For a continuous release of dye at a constant rate $q_i \equiv D_a M_i / t_i$, during the time $0 < t < t_i$, the one dimensional solution is as follows:

For $0 < t < t_i$,

$$c(t) = \frac{D_a q_i}{2Q_\ell} \{ e^{-\frac{K_d x}{\bar{u}}} [2 - erfc(\frac{\bar{u}t - x}{\sqrt{4E_x t}})] - e^{\frac{x\bar{u}}{E_x}} erfc(\frac{\bar{u}t + x}{\sqrt{4E_x t}}) \},$$

and, for $t > t_i$,

$$\begin{aligned} c(t) = & \frac{D_a q_i}{2Q_\ell} \{ e^{-\frac{K_d x}{\bar{u}}} [erfc(\frac{\bar{u}(t - t_i) - x}{\sqrt{4E_x (t - t_i)}}) - erfc(\frac{\bar{u}t - x}{\sqrt{4E_x t}})] \\ & + e^{\frac{x\bar{u}}{E_x}} [erfc(\frac{\bar{u}(t - t_i) + x}{\sqrt{4E_x (t - t_i)}}) - erfc(\frac{\bar{u}t + x}{\sqrt{4E_x t}})] \}. \end{aligned}$$

The time dependent concentrations at the diffuser exits and other locations in the Bosphorus as a result of instantaneous and continuous pulse releases are shown in Figures 5.9 and 5.10 respectively. The concentration time histories are plotted at the three Bosphorus sections located at 5, 15, and 30 km distances downstream from the source respectively, to show the variation along the Bosphorus. In both calculations, adsorption and initial diffuser dilution has been accounted for, and the dispersion coefficient estimated for the case of the August - September 1994 experiment have been used.

The only difference between Figure 5.9 and 5.10 is the decay cofficient for the dye, with $K_d = 0$ in the first case, and $K_d = 0.029$ (half-life $T_d = 24h$) in the second case. Comparison of the two cases gives a clue on including a decay term in the predictions: Without any decay ($K_d = 0$) the solution for the continuous (pulse) injection indicates that there would be no decrase in concentration as the dye moves along the Bosphorus. On the other hand, our measurements (Section 5.9) seem to support a slight decrease of the maximum

concentrations along the Bosphorus in this case, although there is some uncertainty resulting from scatter in the measurements due to insufficient transverse mixing. A decay term with an arbitrary choice of $K_d = 0.029h^{-1}$ was included in all calculations.

The longitudinal dispersion coefficient E_x was estimated from the semi-empirical relationship $E_x \equiv 0.04\bar{u}_\ell \bar{w}_h^2/\bar{h}u_*$ (last section), which depends mainly on the channel geometry. To test the sensitivity of the calculations to geometry, in Figure 5.11a-d, we plot the results from instantaneous release runs with different values of the width and depth of the lower layer. The corresponding dispersion coefficients and Bosphorus dilution ratios are compared in the following:

depth h_ℓ (m)	width w_ℓ (m)	Dispersion Coefficient E_x (m^2/s)	Dilution at North Exit of the Bosphorus $c(L_b,t)_{max}/c_i$
500	30	171	6.5×10^{-6}
700	30	336	3.3×10^{-6}
500	20	241	8.3×10^{-6}
500	40	135	5.5×10^{-6}

The dispersion of dye along the Bosphorus is a strong function of the width and depth of the lower layer. Although constant values are assumed in the above, these parameters are in fact variable along the Strait, as a function of local geometry and internal hydraulics. As a result, we expect that the dispersion coefficient to be variable, $E_x(x,t)$, and the solution will be modified accordingly.

We discuss the experiments of August - September 1994 from the point of view of general features and the sensitivity of predictions. The comparison of the predicted concentrations with the observations, including all four experiments will be made in Section 5.9.

From the above, we pick the case with $E_x = 171$ Figures (5.10 and 5.11.b) to be appropriate for the August-September 1992 case, because good order of magnitude agreement is obtained with the observed concentrations (Section 5.9). However, we point once again to the along Strait variability of the lower layer flow cross-section and curvature, which could lead to lengthwise variations in the concentrations which may not be fully accounted for in the above solutions.

The continuous pulse release was designed to simulate continuous release conditions, and as such to elevate the concentrations to steady-state levels throughout the Bosphorus. With a finite pulse length the steady-state conditions can be approached during the passage of

the pulse at each location along the Bosphorus. It can be seen from Figure 5.9 that for the 17 hour continuous injection, a plateau of nearly constant conditions are reached for a comparable period at each station. With this setting approaching the steady conditions, it would in principle be possible to measure concentrations throughout the Bosphorus with less logistical constraints compared to the instantaneous release case, although the continous release is very costly for the present scales of the experiments, for it would require large volumes of dye released over long periods.

5.7 The Rhodamine-B Concentration Measurements

Experiments of dye dispersion and transport were carried out at three different times during 1992-1993, during which the Bosphorus and the adjoining regions were extensively covered in time and space by CTD measurements of temperature, salinity, and Rhodamine-B fluorescence at high vertical resolution. The dates, types of dye dispersion experiments, and the number of CTD fluorometry casts during these periods are shown in the following table:

Dates of Experiment	Ship	Type of Dye Release	Number of Stations
28 - 31 Aug. 1992	R/V BİLİM	Instantaneous	94
28 - 31 Aug. 1992	R/V ARAR	Instantaneous	77
1 - 2 Sep. 1992	R/V BİLİM	Continuous	44
1 - 2 Sep. 1992	R/V ARAR	Continuous	52
3 - 7 Mar. 1993	R/V BİLİM	Instantaneous	147
3 - 7 Mar. 1993	R/V ARAR	Instantaneous	87
16 - 19 Dec. 1993	R/V BİLİM	Instantaneous	83

Instantaneous and continuous pulse release experiments were done during August - September 1992. The other experiments in March and December 1993 only employed the instantaneous release technique. The station positions during each of the dye release experiments are shown in Figures 5.12 - 5.15.

The continuous fluorescence measurements on board the R/V BİLİM and R/V ARAR were obtained concurrently with temperature and salinity measurements from CTD casts. In addition, in-situ light transmission data were collected on board the R/V BİLİM during the August-September 1992 experiment. The instruments proved to be very accurate in measuring the in-situ Rhodamine-B fluorescence, and during the August-September 1992 experiment, the order of magnitude confirmation of the measurements were provided by two sets of independent, though less accurate, laboratory measurements made from the

numerous water samples collected by the ships. The depth profiles of Rhodamine-B for all stations are given in Volume 3 of this report, along with the simultaneous temperature, salinity (and light transmission, where it exists) profiles.

Before each experiment, the fluorometers were calibrated on board with a number of Rhodamine-B samples in freshwater and sea-water. The background fluorescence for sea-water has been subtracted from the in-situ fluorescence values, and the in-situ values were normalized as described in Section 5.4.

Background Rhodamine-B fluorescence could be detected in in-situ measurements in the sea, even when the above background levels were subtracted according to laboratory measurements with a typical sample of seawater. This background, which can be variable from one place to another, and with time, arises because of the interference at the same light emission wavelengths from other fluorescent materials (*e.g.* chlorophyll, chemicals, etc.) present in the seawater. As a result, the calibrated measurements can indicate small dye concentrations even before any dye is introduced. To eliminate this type of background in the measurements, pre-discharge surveys were ususally conducted.

The measurements in the Bosphorus showed small values of the background fluorescence, except that it generally differed between the upper and lower layer waters. This background fluorescence was corrected in all of the subsequent measurements, by making a correlation of background concentration with salinity (Figures 5.16 - 5.18). A piecewise linear approximation to the background concentration versus salinity was then made and the amount proportional to the salinity of a particular measurement was subtracted from the measured concentration. Despite these background corrections, it can be verified from Figures 5.16 - 5.18 that typically, an uncertainty on the order of $0.1ppb$ would remain in the dye measurements. This small background can be observed in the concentration profiles displayed in Volume 3 of the report.

Overlooking the spatial variability of the background, and accounting for it by the salinity correction alone, occasionally led to undesirable effects, when some understanding of the distribution was not available. For example, in August 1992, the background measurements only covered the Bosphorus, did not cover the adjacent Black Sea and the Marmara Sea regions. Because the pre-injection measurements in the Bosphorus indicated negligible background levels, we proceeded with the actual dye release experiments. Evidently this resulted in a deficiency in the understanding of the background in the adjoining regions, because relatively large concentrations, which we believe were related to the background, were observed in these waters after the injection. Similarly, high background values were found in these regions in the later experiments.

During December 1993, the background concentrations measured in the Marmara Sea entrance (16 December) and the Bosphorus regions (17 December) prior to dye release

differed in character, yielding two different background concentration versus salinity curves shown in Figures 5.18a and 5.18b. The differences in could be the result of variable flow conditions during the Orkoz event that developed in the same period (Chapter 3). Because we wanted to compare the results to each other during the same cruise the second curve (Figure 5.18b) was used for applying corrections to all the profiles (Volume 3), which left some upper layer background, but eliminated it in the lower layer concentrations in the Marmara Sea profiles.

Although the Chelsea Acquatracka III fluorometers with appropriate filters were coupled with the CTD profilers on board the two ships, independent laboratory measurements of Rhodamine-B fluorescence were also made at a few stations, to confirm the CTD fluorometry results, using water samples collected with Nansen bottles on the R/V ARAR and a rosette sampler on board the R/V BİLİM. The Laboratory fluorescence measurements were made on two independent spectrofluorometers located at the İSKİ and IMS-METU Laboratories. Although the laboratory fluorometers turned out to be sensitive instruments, the fluorescence measurements from water samples were expected to be less accurate than the CTD fluorometry, because of the possibility of errors during sampling and preservation of the water samples. The results of laboratory measurements in August-September 1992 are given in Table 5.1, and the data points with significant fluorescence values during these first experiments are displayed in Volume 3, along with the CTD dye concentration profiles. Considering the possible sources of error, the laboratory measurements in general agree with the on-board measurements and yield valuable confirmation of the CTD fluorescence measurements.

At some stations, *E. Coli* counts were made to verify the presence of waste discharge along with fluorescence measurements. The values listed in Table 5.1 indeed verify that the *E. Coli* counts were significantly higher at stations where we detected large concentrations of Rhodamine-B.

5.8 Analyses of the Rhodamine-B distribution

The Rhodamine-B profiles in Volume 3 are the basic measurements of dye distribution obtained during the various dye release experiments. However, since they are not readily available for interpretation in this form, we processed these data to extract quantitative information on the effects of waste disposal.

One of the basic assumptions used in the design of the wastewater disposal system is that the wastewater would be discharged to the lower layer of the Bosphorus currents transporting the Mediterranean Water to the Black Sea. Indeed the Bosphorus salinity distribution (Volume 3) clearly indicates that there are two main layers: an upper layer, carrying Black Sea Water and a lower layer carrying Mediterranean water. These layers are

seperated by an interface, or *i.e.* more accurately, an interfacial layer of $\sim 10\ m$ thickness, where there is a sharp salinity (and density) gradient.

An interpretation of the measurements could be approached by defining the flow structure within the Bosphorus with respect to the water types. On the other hand, the characteristics of each water type changes from one location to the other, even within the survey area, so that local definitions seem to be needed. We defined the characteristic upper layer salinity S_s as the 5 m depth average of the near surface waters, and the characteristic lower layer salinity S_b as the 5 m depth average of the near bottom salinities at each station. We did not consider the stations where the characteristic salinities were ill-defined, *i.e.* where $S_s > 20$ and $S_b < 30$ (*i.e.* salinities much lower, and much higher than the typical Black Sea and Mediterranean waters respectively), resulting from sampling problems or location of the stations not covering both layers adequately. Defining $S_1^* = S_s + 0.2(S_b - S_s)$ and $S_2^* = S_2 - 0.2(S_b - S_s)$ as limiting values to differentiate the Black Sea and Mediterranean water types, we defined the upper layer to consist of those waters having a salinity $S < S_1^*$, the intermediate layer to consist of those with $S_1^* < S < S_2^*$, and the upper layer to be those with $S > S_2^*$. Having defined the salinity limits as such, we then integrated the Rhodamine-B concentration in each layer and found the three-layer average concentrations for each CTD station. Since the background levels of Rhodamine-B were about $< \pm 0.1 ppb$, average concentrations less than these threshold levels were set equal to zero.

For all experiments carried out to date, Tables 5.2a-c list the CTD station information (name, date, time, latitude and longitude, bottom depth) and the surface and bottom salinity, along with the average Rhodamine-B concentrations $\bar{c}_1$, $\bar{c}_2$, $and \bar{c}_3$ respectively in the upper, interfacial and lower layers.

5.8.1 The Exit and Average Concentrations near the Diffuser

After instantaneous dye releases, both the BİLİM and the ARAR attempted to sample near the source (near station B0, Table 5.2.a-c), in spite of the difficulties of sampling within the spatially inhomogeneous discharge plumes. Some of our measurements indeed showed high concentrations near the source (Tables 5.2a-c), whenever a sample could be obtained directly from the diluted wastewater plumes.

The measurements are compared with estimates in the following table. The maximum of all concentration measurements near the source (measured c_d) is compared with its estimated value from $c_d = D_a D_d c_i$, where $D_d = 0.02$, and the adsorption ratio was taken as $D_a = 0.5$ for the first three experiments (Aug. 1992, Sep. 1992 and Mar. 1993) and $D_a = 0.25$ for the last one (Dec. 1993). The maximum of the average lower layer concentration c_o based on measurements given in Tables 5.2.c are then compared with the calculated average concentration $c_o = c_\ell Q/Q_\ell$, where Q/Q_ℓ is the ratio of the pipeline discharge to the estimated Bosphorus lower layer discharge.

Date	dye exp.	tank conc. c_t (ppm)	calc. diff. conc. c_d (ppb)	meas. diff. conc. c_d (ppb)	waste water flux Q (m^3/s)	l. layer Bosphorus flux Q_ℓ (m^3/s)	calc. source conc. c_o (ppb)	meas. source conc. c_o (ppb)
Aug. 1992	Inst.	200	2000	80	2	7500	54	52
Sep. 1992	Cont.	1.7	17	10	2	12000	1	4
Mar. 1993	Inst.	260	1300	64	6	5000	31	21
Dec. 1993	Inst.	345	1700	108	2	19000	36	79

The measured maximum diffuser concentration is often much smaller than the estimated value because of sampling constraints and the variability near the diffuser source. The order of magnitude agreement between the estimated and the measured maxima of cross-sectional average concentrations is far better.

5.8.2 Concentrations in the Bosphorus and Marmara

The overall ranges of Rhodamine-B concentrations observed in the Bosphorus and the adjacent waters are displayed in the following figures.

Figures 5.19 - 5.22 show the variation with time of the average concentrations (Table 5.2.a) in the upper, interfacial and lower layers respectively, during the August - September 1992 experiments. Each figure includes the data from the instantaneous and continuous release experiments combined together, and with the time of observation adjusted relative to the time of exit from the diffusers. The upper and interfacial layer concentrations are 4ess than about 0.5 ppm, while the highest mean concentrations are observed in the lower layer waters (Figure 5.20), with a maximum of about 53 ppb near the source. Since most lower layer data in this last plot are invisibly smaller, relative to the maximum, we give a plot with expanded scales in Figure 5.21 to display partial data which fit on that scale.

The upper layer concentrations in Figure 5.19 indicate some data points with concentration < 0.5 ppb, but higher than the selected threshold level of $0.1ppb$, as well as some data with zero concentration because values below the threshold levels were set equal to zero. We can also note that most of the data above the threshold level were obtained by R/V ARAR, *i.e.* in the Marmara Sea region adjacent to the Bosphorus. It is here that we suspect the background levels were rather high, and therefore did not fit in the threshold levels we defined based on background measurements. It can also be noted that the mean levels of these data points stay constant with time, and include some data points before the injection times (negative time), consistent with background behaviour.

The interfacial layer (Figure 5.20) includes some data points with the above background characteristics, as well as what we think are genuine increases of concentrations in the interfacial layer observed in the Bosphorus (R/V BİLİM) and Marmara waters (R/V ARAR).

In contrast, the lower layer concentrations (Figures 5.21 and 5.22) decrease rapidly with time due to dispersion along the Bosphorus, and fall below the threshold levels within a period of 36 hours from the injection time.

During the March 1993 experiment (Table 5.2.b), we find that the upper layer measurements obtained by R/V ARAR in Marmara Sea indicate large background concentrations of Rhodamine-B before the dye was injected (time < 0, Figure 5.23), and no detectable levels afterwards (time > 0, Figure 5.23, and Table 5.2.b), except at a very few stations. The R/V BİLİM measurements during dye release indicated very small upper layer concentrations, of which, a few exceeeded threshold levels of 0.1 *ppb*.

In contrast, the interface layer concentrations in March 1993 indicated a number of measurements with concentrations reaching 1.0 *ppb* (Figure 5.24), and a few that reached 2 *ppb*. Some of these measurements were obtained by R/V ARAR before the dye injection in the Marmara Sea, but a few others obtained in the Bosphorus by the R/V BİLİM following dye injection also had similar concentrations.

In comparison, the lower layer dye concentrations in March 1993 (Figure 5.25) were much higher, reaching up to 20 *ppb* after dye injection.

In December 1993, the identification of three layers was less straightforward because of the special flow conditions in the Bosphorus, when the upper layer was actually blocked under Orkoz conditions, and was not flowing into the Marmara Sea. The water layer containing Black Sea water of low salinity ($S < 18$) was found (Table 5.2.c) only north of Station B-14 and B-15 near the north end of Bosphorus on 17 December when the background measurements were done, and receded to mid-Bosphorus constriction area (north of Station B-6) during the dye measurements on 18 December. The other stations indicated Marmara surface water ($S \simeq 24 - 26$) flowing towards the Black Sea and submerging under the low salinity wedge of Black Sea water when the latter existed at a particular locality. Under the Marmara surface water was the usual Mediterranean (Marmara lower layer) water, separated from the overlying layer by an interface layer. Therefore the three layers distinguished by our detection and analysis algorithm in the southern part of the Bosphorus were all being advected from Marmara. On the other hand, northward of the low salinity wedge, in five layers would exist according to this classification: the Black Sea surface water, a first interface layer, the Marmara surface water, a second interface, and the Mediterranean water. But in this case the surface and bottom slinities detected by the algorithm were the Black Sea and Mediterranean waters, so that the three layers corresponded to these and an interface in between them.

With the above considerations in mind, the December 1993 results indicated conditions similar to the earlier dye experiments, even under the adverse effects of Orkoz: The upper layer concentrations were mostly below $0.5ppb$ (Figure 26), representing a slight increase relative to earlier experiments. The interface mostly had similar values (with just two values exceeding $0.05ppb$, Figure 5.28), and the lower layer average concentration (Figure 5.28) reaching $80ppb$ initially near the source decreased rapidly with time along the Bosphorus.

The spatial distributions of the layer averaged concentrations for the entire region during each experiment are presented in contour plots in the following Figures. As the previous figures (Figures 5.19 - 5.25) were used to display the layer concentrations as a function of time only (irrespective of space), these figures (Figure 5.29 - 5.40) show the spatial distribution without distinction of the time of measurement.

Figures 5.29 - 5.32 present results for the instantaneous release, while Figures 5.33 - 5.36 present results for the continuous pulse release during the August - September 1992 Experiment. The surface salinity distribution during the instantaneous release experiment (Figure 5.29) indicates large horizontal gradients in the southern Bosphorus due to vertical mixing. The surface waters exit into the Sea of Marmara in the form of a surface jet extending south from the Bosphorus. The upper layer dye concentration in Figure 5.30 indicates a maximum near the west coast of the Bosphorus exit, decreasing steadily towards the Anatolian coast. The upper layer dye concentrations within the Bosphorus are much lower than the Marmara concentrations, and in fact lower than the threshold. The tongue-like extension from the Bosphorus into the Marmara Sea may be related to the jet issuing from the Bosphorus, where the fluorescence anomaly in fact reaches a minimum rather than a maximum, opposite to what one would expect if entrainment from the lower layer to the upper layer was responsible for the observed levels in the Marmara Sea region. We therefore beleive that the fluorescence levels observed in the Marmara region are related to a spatially variable background rather than an increase due to entrainment processes. As it has already been discussed, this background could arise from a spectral interaction of fluorescent materials present in the seawater with our detection wavelength for Rhodamine-B. The shallow region west of the Bosphorus exit where we find the maximum is an anchoring area for ships, and is heavily polluted. We can therefore suspect a background effect, but since background measurements were not made in this region, we can not substantiate this possibility with positive proof. On the other hand, background measurements obtained during the experiments later in March and December 1993 confirm the existence of variable background in these regions prior to dye injection (see below).

The interfacial layer concentrations (Figure 5.31) are at the same levels and have similar features as the upper layer waters. The lower layer concentrations (Figure 5.32) are only high within the Bosphorus, and no detectable levels can be found on the Marmara side.

In comparing the continuous pulse release with the instantaneous release, we find similarities especially in the Marmara region. The surface salinity in Figure 5.33 reveals reduced values resulting from the typical exit of the Bosphorus jet. The upper layer dye concentration in Figure 5.34 is of the same levels and a similar distribution to that observed during the instantaneous release experiment (Figure 5.30). The interfacial layer distribution (Figure 5.35) is also of similar levels, and the lower layer distribution (Figure 5.36) is limited to the Bosphorus region.

In March 1993, the surface salinity plotted in Figure 5.37 for the periods before and after the dye injection attests to the variable flow conditions during this experiment. The upper layer dye concentration in 5.38 indicates high background levels in most part of the Marmara Sea, which decreased after the injection, except in the western part. The pattern for the interfacial concentration was the same: large values were found in parts of Marmara Sea before the injection, which disappeared after the injection (Figure 5.39). On the other hand, no dye was visible in the lower layer before the injection, which increased near the diffusers after the injection (Figure 5.40).

In December 1993, the upper layer waters in Marmara displayed high concentrations before the dye injection (Figure 5.41), while it was not present in the interfacial and lower layers (not shown, Table 5.2.c).

The observation of variable levels of spatially inhomogeneous fluorescence in the Marmara upper layer and interfacial layer, persisting before and after the dye releases reinforces further our contention that this fluorescence is mostly due to sources other than the injected Rhodamine-B. Firstly, different amounts of dye (180 kg, 408 kg, 312 kg and 312 kg during August, September 1992, and March, December 1993 experiments respectively) were injected in the various experiments, and there seems to be no correlation of the dye with the observed variable background in the Sea of Marmara. For example, during the two dye release experiments in August-September 1992, the apparent concentrations in the Marmara surface and interfacial waters remained roughly the same. On the other hand, in March 1993, higher concentrations in the surface and interfacial layer waters were observed before the dye release, as compared to those after the injection. In December, 1993, similar high concentrations existed in Marmara before the dye release.

A simple calculation shows that the background levels observed in the Marmara waters were anyhow much larger than that would be induced by entrainment into the upper layer. For example, for the case of August - September 1992, taking a total depth of 30 m for the upper and interfacial layers, and a mean concentration of 0.3 ppb in the area covered by our measurements (an area roughly 5 km by 5 km in size, we find a total dye content of 225 kg, which would be of the same order as the dye injected in either of the two experiments. Taking into consideration that the dye patch would not be limited to this area alone, this figure is much higher than that can be accounted for by any physical mechanism of

dye entrainment into these waters. This result does not mean, however, that there was no dye introduced into the upper and interface layer waters. Rather it implies that the background levels were probably too high to detect any dye coming from the entrainment of a lower layer injection into at the diffusers.

5.8.3 Maximum Layer concentrations

A discussion of the maximum concentrations measured in the Bosphorus during each experiment can be helpful. The following table gives the maxima of the layer averaged concentrations, and the overall maxima of all single measurements of concentration within each layer.

Date	exp.	max. of avg. u.l. conc. $(c_1)_{max}$ (ppb)	max. of avg. i.l. conc. $(c_2)_{max}$ (ppb)	max. of avg. l.l. conc. $(c_3)_{max}$ (ppb)	max. of all u.l. conc. $(c_{max})_1$ (ppb)	max. of all i.l. conc. $(c_{max})_2$ (ppb)	max. of all l.l. conc. $(c_{max})_3$ (ppb)
Aug. 1992	Inst.	0.16	0.63	52.3	0.75	0.68	81.6
Sep. 1992	Cont.	0.29	0.41	3.8	0.75	0.46	10.2
Mar. 1993	Inst.	0.18	0.92	21.0	1.45	5.76	63.8
Dec. 1993	Inst.	0.38	1.56	78.9	0.55	4.92	109.1

It is seen that the layer averages of concentration in the upper layer of the Bosphorus (not including the Marmara exit region) were at all times less than 0.4 *ppb* regardless of the date and type of experiment. The interface layer concentrations were a little higher, with average concentrations not exceeding 1.5 *ppb*, even when the lower layer concentrations reached high values on the order of 100 *ppb* (and even possibly hiher, of *ppm* levels, considering diffuser outlet concentrations predicted, but not measured due to sampling constraints).

5.9 Longitudinal Dispersion along the Bosphorus

The dispersion of dye along the Bosphorus was followed by the R/V BİLİM in all of the experiments. Since the total time of transit through the Bosphorus is short, the measurements required a special sampling strategy. In the case of instantaneous releases, the calculations (Figures 5.9 - 5.11 in Section 5.6) typically indicated that the time overlap of concentration curves between sections located at three positions along the Bosphorus,

for example at distances of $\sim$ 5, 15 and 30 km away from the diffuser source would be reasonably short, so that separate time series measurements could be made at each of these sections by the R/V BİLİM.

The three locations at which to obtain time series of layer averaged concentrations in a feasible way were decided to be the vicinity of stations B5, B8 and B-15, located approximately at 7.5, 15 and 28 km downstream of the diffuser source. In addition to the detailed sampling near these stations, measurements were carried out at other stations along the Bosphorus, whenever there were opportunities for the ship.

After instantaneous dye releases, both the BİLİM and the ARAR attempted to sample near the source (near station B0, Table 5.2.a-c), in spite of the difficulties of sampling within the spatially inhomogeneous discharge plumes. Some of our measurements indeed showed high concentrations near the source (Tables 5.2a-c), whenever a sample could be obtained directly from the diluted wastewater plumes.

After sampling at the source region, typically the BİLİM moved to station B5, and obtained repeated profiles across the cross-section to construct a time-series of fluorescence, temperature, salinity and current profiles. While BİLİM waited for the dye patch to arrive at B5, the MURAT REİS went between stations B0 and B5 to monitor the dye patch. It then stayed near station B4, southwest of station B5 and near the west coast of Bosphorus, to detect the dye patch before it arrived to the nearby B5 section. It was often found the MURAT REİS detected dye concentrations at B4, while no dye was found by BİLİM at B5. The difference was confirmed by measurements repeated by BİLİM at station B4 (Table 5.2.a).

The trapping of dye near station B4 is not surprising. This region of Bosphorus, *i.e.* the western flank from the Haliç to Beşiktaş is a widening area of the strait separated by a shallow sill structure from the main channel, and recirculations are known to occur (*e.g.* Özsoy *et al.*, 1986) in this region. In fact, there are two separate channels one east and the other west of the shallow bottom topgraphy near station B4. The channel cross section at B5 is more uniform, though the measurements there could be affected by the topography upstream of the lower layer flow. The dye patch at stations across the B5 section was never uniform (Figure 5.15) because of relative closeness of this section to the diffuser sources and in view of the fact that the transverse mixing time scales were estimated to be quite long (Section 5.6).

The measurements at other stations in the southern Bosphorus typically indicated a high degree of inhomogeneity in the dye distribution, both in the vertical and in the horizontal. Homogeneity was achieved only in the northernmost end of the Bosphorus, as it has been predicted in the Section 5.6.

We compare the measured concentrations along the Bosphorus with the londitudinal dispersion predictions based on Section 5.6. The computations were made with the following parameters, and specifying the source concentrations as described earlier for each experimental case.

Date	dye release	mean current $baru_\ell$ (m/s)	depth h_ℓ (m)	width w_ℓ (m)	Dispersion Coefficient E_x (m^2/s)	Adsor. Ratio D_a	Figure No.
Aug. 1992	Inst.	0.50	500	30	171	0.50	
Sep. 1992	Cont.	0.60	500	30	205	0.50	
Mar. 1993	Inst.	0.30	400	25	90	0.50	
Dec. 1993	Inst.	0.45	400	25	138	0.25	

Several simplifying assumptions assumptions have been made in calculating the predicted concentration: the adsorption ratio, dye decay, and the width, depth and velocity of the Bosphorus lower layer have been estimated based on a simplified, average knowledge of these complex factors. Furthermore, an average triangular cross-sectional geometry of the Bosphorus with constant area and depth below the interface has been assumed, and the semi-empirical relationships of Section 5.6 have been used to estimate the longitudinal dispersion coefficient used in the calculations. Estimates of all of these parameters could change in some range based on subjective judgements. In addition, the actual flows in the Bosphorus are variable in space, and in time, even within the duration of a single experiment. Further, the measurements also contain some errors deriving from sampling, calibration, background corrections, and vertical averaging.

In spite of the simplifying assumptions, considerable success is obtained in comparisons of measured concentrations with the simple model calculations based on above. The time histories of concentration at three locations along the Bosphorus are shown in Figures 5.41-5.45 for the four different dye release experiments. In each of the three displays in each Figure, the measurements of lower layer average concentration (Tables 5.2a-c) have been grouped around stretches of the Strait centered around staions B5, B8 and B15 respectively located about 7.5, 15 and 28 km downstream of the source, by allocating to a particular position the casts obtained in the respective distance ranges of 5-10 km, 10-21 km, and 21-33 km. For comparison, the time histories of concentration obtained from the simple models, using the above parameters, are plotted on the same figures.

Comparing the concentration levels near the B5 section (at 7.5 km, the top display) in Figures 5.42, 5.44 and 5.45, with the source concentrations c_o given earlier, it can be verified that in the instantaneous release case, the concentration decreases by about an order of

magnitude within this distance. Comparing them with the maximum dye concentration c_d at the exit of the diffusers, it is observed that the dye is found to be diluted by three orders of magnitude until reaching the vicinity of station B5, about 4-6 hours later.

In continuous release case (Figure 5.42) the dye concentration along the Bosphorus decreases only slightly (at a much slower rate compared to the instantaneous release case), because it is reduced mainly by the decay processes, which parameterizes the sum of photochemical decay and losses to the upper layer, as has beeen explained earlier. The value of the decay coefficient has been set to some value based on the arguments given earlier. Given the scatter in the measured values, the choice of $K_d = 0.029$ (Sections 5.3 and 5.6), used in the calculations is somewhat arbitrary.

In addition to the comparison of measured and computed time histories of concentration, which provides a means for testing the semi-empirical dispersion coefficients used in the calculations, attempts to use some independent methods were made to determine the dispersion coefficients from the data. In actuality we expect the dispersion coefficient to be variable with the three-dimensional flow and diffusion patterns, as well with distance along the Strait, because the geometrical and flow characteristics change with distance.

One of the standard methods to determine the longitudinal dispersion coefficient is to make plots of concentration with respect to distance and time. In the instantaneous relase case, it is best to use the transformed coordinate ζ to represent distance and time together, and to plot concentration in logarithmic scale so that all measurements can be represented on a single plot. We first divide the instantaneous source solution $c(x,t)$ by some reference concentration $c_* = c(x_*, t_*)$ and transform it into the following form:

$$ln\left\{\left(\frac{c(t)}{c_*}\right)\sqrt{\frac{t}{t_*}}\right\} = -(\zeta - \zeta_*),$$

where

$$\zeta = -(x - \bar{u}t)^2/4E_x t - K_d t$$

and $\zeta_* = \zeta(x_*, t_*)$. Plotting in the above coordinates would then yield a slope of -1 if all the data are consistent with the instantaneous source solution. However, in order to make such plots we must give $\bar{u}$ and E_x values as inputs, which we can vary until obtaining a slope of -1.

Because the values $\bar{u}$ and E_x are expected to be variable along the Strait, we could not collapse all the data to a single plot, and separated the data to correspond to southern and northern Bosphorus by grouping them into distance ranges of 5 - 10 km and 10 - 33 km respectively. This is done in Figures 5.46a,b and 5.47a,b for the instantaneous release experiments of August 1992 and March 1993 respectively.

The $\bar{u}$ and E_x values adopted to give straight line dependence of slope -1 for the southern and northern Bosphorus regions were ($\bar{u} = 0.3m/s$, $E_x = 150m^2/s$) and ($\bar{u} = 0.6m/s$, $E_x = 400m^2/s$) for the case of August 1992 (Figures 5.46a,b), and ($\bar{u} = 0.5m/s$, $E_x = 150m^2/s$) and ($\bar{u} = 0.3m/s$, $E_x = 200m^2/s$) for the case of March 1993 (Figures 5.47a,b). These are in order of magnitude agreements with the estimates of current speed and longitudinal dispersion coefficients used in the time history calculations in Figures 5.42 - 5.45, and diplayed in the earlier table. However, there is more than one degree of freedom in adjusting the curves to a slope of -1, because $\bar{u}$ and E_x are two free parameters. The criteria used in the adjustments were therefore the achievement of less scatter and a better fit to a linear slope.

5.10 Calculation of Dye Fluxes across the Bosphorus

The simultaneous measurements of current velocity and Rhodamine-B dye allow the calculation of dye fluxes across the Bosphorus, and such calculations were the ultimate aim of the experiments. The instruments used were selected specificly for this purpose, allowing rapid and accurate data collection during the transit time of a dye patch through the Bosphorus.

Although the coverage of the entire Bosphorus, or some critical sections with high resolution measurements would ideally yield the desired information, the fluorescence and velocity measurements can not always be carried out with sufficient area coverage and in perfect synchronization, as a result of the experiment logistics and actual sampling conditions. With the methodology we developed especially for the Bosphorus, the ADCP measurements can be obtained rapidly and with sufficient resolution (depth profiles with 1 m vertical resolution obtained at 30 s time intervals) across any cross-section of the strait, but the instrument limitations cause some loss of data very near the surface (comparable to the depth of the ship keel) and near the bottom (for the region about 15 % of total depth above the bottom). The required manouvering space for the ship nearshore also leaves some areas uncovered by the measurements. These data gaps are later covered by suitable extension procedures in the computations. The fluorometric measurements obtained during CTD casts have better than 1 m resolution, but since CTD casts require the ship to be held at a fixed position for about 20 - 30 minutes, traffic conditions and drift in the ship's position occuring during the casts can practically allow not more than three different CTD casts on each cross-section.

The CTD casts and ADCP transects can not be done simultaneously, because CTD casts require stationary measurements, while the ADCP transects require the ship to move steadily across the section for reasons of computational accuracy. As a result, the ADCP transects were done separately before or after the CTD casts. However, ADCP data were also collected during each CTD cast when the ship was stationary, and these provided additional data.

The simultaneous CTD and ADCP data at CTD stations do not allow dye flux calculations across the Bosphorus cross section because they are only local. However, these data can be used to compute a depth integrated flux at the particular station, presented in Tables 5.3a-c for the three experimental periods. The ADCP data corresponding to the particular CTD cast have been searched automatically from separate records of the two instruments, and when data from both were available, they have been matched to make a flux calculation. The ordering of the data in Tables 5.3a-c with respect to time is the same as the CTD stations listed in Tables 5.2a-c. In these calculations, the product of the velocity and Rhodamine-B concentration has been integrated vertically for each of the layers identified in Tables 5.2a-c, and divided by the depth of each layer to obtain the dye flux per unit area. The fluxes are calculated in the direction that maximizes the sum of squares of the current speed data versus the depth. The corresponding direction angle, listed in Tables 5.3a-c, is often close to the angle of the normal defining the Bosphorus cross section at the particular location. These calculations are only made to demonstrate the orders of magnitude of the fluxes. Rough estimates of the total dye fluxes across the corresponding Bosphorus cross-sections can be obtained by multiplying the flux figures in Table 5.3a-c by the estimated average width for each layer.

The dye flux calculations based on ADCP transects across the Bosphorus and available CTD data provide a better description of the transverse variations of velocity and dye concentrations, and should thus yield more accurate estimates of the fluxes. Since these data are not synchronous, and numerous repeated profiles of ADCP pings and CTD Rhodamine-B casts were available, a special search had to be made to locate the CTD data closest in time and space to the particular ADCP ping in a transect. If no nearby CTD casts were available, the concentration data was interpolated from the two closest CTD casts on either side of a ping location. The ADCP data were extended uniformly to the surface (with a constant value for the current velocity), and linearly to the bottom (where the velocity is assumed to approach zero) from the closest data point, in order to fill the data gaps in the data devoid regions. The dye concentration data were extended uniformly to the surface, but when data were not available near the bottom, a linear variation from zero at the bottom to the depth of the nearest data was assumed to interpolate the concentration. Banks were assumed to be within 100 m distance from the nearest ADCP ping nearshore, and both velocity and concentration data were uniformly extended in the extended regions of linear depth variation. The data were divided into three layers based on salinity values,

as described previously, and the product of the concentration with the velocity component normal to the cross-section was integrated across the cross-sectional area of each layer.

The results are presented in Figures 5.48a-i, 5.49a-n, and 5.50a-d respectively for the periods of August-September 1992, March 1993 and December 1993, showing the location of the ADCP ping across a transect (+ signs), the depth profile of Rhodamine-B concentration used at the location of each ping (continuous line shading), the depth profile of current velocity normal to the section (dotted line shading) and the positions of the three layers identified from the corresponding salinity data (horizontal lines). The salinity data from the CTD instrument are not shown, but have been used in the computations. The date and time for each ADCP transect, the scales for depth and concentration are shown at the top of each section. The angle 'alpha' noted in each figure is the angle of the normal to the section measured from east, and calculated by maximizing the sum of squares for all normal velocity data in a cross-section. The normal found by this calculation is usually aligned with the Bosphorus channel. The cross sectional area computed respectively for the upper, interfacial and the lower layers are listed in the lower right hand corner for each figure, followed by the integrated water and dye fluxes for each layer.

Notice that the concentration profiles used in the flux computations have small negative values as well as positive values in the surface layer, because of the background effects which could not be eliminated in the measurements. When there is a significant amount of dye (*i.e.* in the interface and lower layers), the concentration values are always positive, as they should be. We did not set the negative concentration values to zero because they represent statistical, though fictitious, deviations of the background from zero, and setting them to zero would bias the surface flux computations.

During the instantaneous release experiment of August 1992, the continuous flux measurements for calculating the transport were essentially made at the B5 Section, and will be described in the next Section. Other flux measurements were done before and after the dye release, but they indicated small values of fluxes associated with background levels.

The measurements made at section B0 during the continuous pulse release in September 1992 indicated large concentrations near the source region, and the flux computations in Figure 5.48a therefore yielded large fluxes for the lower layer. Note that some dye is also found in the surface and the interfacial layers. Because of cumulative effects, it is not clear whether this dye distribution is a result of residuals from the instantaneous release performed three days earlier, or the dye from the continuous release. However, the interfacial dye concentrations in the continuous release case persist throughout the Bosphorus and are also found near the Black Sea exit (Figures 5.48a-i). The surface concentrations are of the background levels through much of the Bosphorus, except at the B0 section. The dye fluxes for the surface and interfacial layers were small when compared to the lower layer fluxes, which were detected at significantly higher values throughout the

Bosphorus. The interface dye and water fluxes are always towards the north (positive), showing that the net motion of the dye at the interface is towards the Black Sea, albeit slower than the lower layer dye distribution. The northward flow of the interfacial waters during this period is consistent with the increased lower layer fluxes during the same period (Section 3).

The continuous dye flux measurements performed during the March 1993 experiment following the passage of dye through Section B5 will be described in the next section. The other flux measurements at several sections are shown in Figures 5.49a-o. Although large amounts of dye were present in the lower layer in most of the Figures, very little transport is found from the flux calculations, as a result of the lower layer flow blocking during 5-7 March 1993 described in Section 3. In the surface layer, some cases yield relatively large flux values when measurable concentrations are multiplied by the large surface currents (*e.g.* Figures 5.49a-d). However, the presence of negative concentrations in other cases (*e.g.* Figures 5.49e-n) suggests that the surface concentrations in these cases are again associated with background effects.

Figures 5.50a-d show dye flux calculations during the December 1993 experiment. Because sections B5 and B8 were done before the arrival of the dye, Figures 5.50a,c show very little lower layer fluxes, while the shallowness of the B4 Section (Figure 5.50b) results in a small flux value in the lower layer. In the first two cases (Figures 5.50a,b) the upper layer corresponds to the Marmara surface layer which flows towards the Black Sea, opposite to its normal direction of flow. There were relatively large dye concentrations in this layer, though not exceeding 0.5 *ppb*, but it is quite possible that the origin of this surface dye concentration during the adverse flow conditions, was not the entrainment from below, but rather the dye leak that occurred to Marmara surface waters during the injection. Indeed the surface and lower layer concentrations appear to be disconnected by an interfacial zone of zero concentration.

At section B8 and B8x (Figures 5.50c,d), the flow was already reversing towards the Marmara Sea when we made the measurements. The wedge of Black Sea water which was pushed to the north end of Bosphorus during 17 December 1993 returned back to a position near station B7 located at the constriction, during 18 December. The front of the wedge was very close to section B8 (Figure 5.50c), where the surface flows were arrested; but larger flows of the Marmara surface waters submerging under the Black Sea wedge were carrying dye from Marmara towards the Black Sea in what became the interfacial layer at this Section. The fluxes in the interface layer (Marmara upper layer) and the lower layer (Marmara lower layer) are large when the dye is passing through sation B8x (Figure 5.50d), while there is practically very little dye in the upper layer (Black Sea water).

5.11 Calculations of Net Dye Transport

In addition to flux computations across a section at a given time, the data permit us to make computations of total dye mass passing through a given section after a dye release. This requires continuous monitoring of dye at a particular station, and is therefore limited by the time that could be spent at a fixed location by the ship. The B5 cross-section was selected for this purpose during the instantaneous release experiments. The ship occupied different positions across the B5 cross-section, as much as it was allowed by the difficult maneouvering conditions at different times after the releases.

The positions of the CTD casts taken from the ship during this dye flux monitoring exercise in August 1992 are shown in Figure 5.51, plotted along distance coordinates parallel and perpendicular to the section respectively. In Figure 5.52, the positions across the B5 section during the same experiment are plotted against time. Figure 5.53 gives the station positions in the experiment of March 1993.

The procedure for the transport calculations was as follows: The ctd casts were divided into groups according to 'time slices' so that they would reasonably cover the cross-section for a given slice (dotted lines in Figures 5.52 and 5.53), then the procedure outlined in the last Section was used for calculating fluxes for each time slice, *i.e.* matching the nearest CTD cast with the individual ADCP pings. Because of the logistics of the experiment, a single ADCP transect could be made before the monitoring period, and these velocity data were used in all of the subsequent calculations. High values of lower layer dye fluxes are found throughout the monitoring periods, with essentially zero surface and interfacial fluxes.

Finally, the flux values found from each time slice are multiplied with the corresponding time interval, and summed up to yield the total mass of dye transported through the cross-section. The calculations are presented in Tables 5.4.a and 5.4.b respectively for the August 1993 and March 1993 instantaneous release experiments.

It is found that a total dye mass of 54 kg passed in the lower layer flow through the B5 section in the August 1992 instantaneous release, and 62 kg during the March 1993 case (Tables 5.4.a and 5.4.b). These are quite reasonable values of the total transport found from time and space integration of dye fluxes, given the measurement uncertainties and assumptions used in the computations.

In the August 1993, the total mass of dye released was 180 kg. Allowing for an adsorption loss of 50 % in the tanks and through the diffusers, it is estimated that 90 kg of pure Rhodamine-B in solution would be released into the Bosphorus from the diffusers. Allowing for chemical or entrainment decay with $K_d = 0.029h^{-1}$ as used in section 5.6, would reduce this amount by another 10 %, in the 4 hr time period for the dye to reach Section B5,

giving 81 kg as an estimate of the amunt of dye that should pass from this Section. It can thus be inferred from this calculation that a high percentage ($\sim$ 67 %) of the total dye would have actually passed through the Bosphorus at Section B5, if all the measurements and calculations were correct.

In the case of March 1994, the total mass of dye released was 312 kg. Similarly allowing for an adsorption loss of 50 %, and a decay loss of 10 % would yield an estimate of 140 kg of Rhodamine-B to pass Section B5. The integrated mass of 62 kg obtained by measurement would represent $\sim$ 23 % of the estimate.

The reason for a larger disagreement of mass transport in the second case may be the increasing inaccuracies in the flux estimations, since most of the information near the bottom was misssed because the lower layer flow was essentially very close to being blocked during this survey.

Once again we emphasize the various approximations used in the calculations, and the sources of measurement errors in the above calculations: (1) the adsorption ratio is largely uncertain because it depends on the turbulent interactions between the wastewater and the dye during preparation and injection, as well as on the pipeline flow and the sediments carried in the flow; (2) the vertical and horizontal inhomogeneities of dye and current distributions at Section B5, gives rise to large uncertainties in the dye fluxes; (3) the loss of current and concentration data near the top and bottom 15 % limits of total depth not resolved by the ADCP and by lowering restrictions of CTD profiler, and near the two flanks of the Bosphorus channel due to manouvering restrictions are compensated by extension procedures; (4) the time resolution and period of mesurements can cause additional uncertainties.

The order of magnitude agreement between the calculated and measured transports is considered to provide a successful and solid confirmation of the main results reached within this dye study, despite all the possible sources of uncertainties.

5.12 Conclusions

Dye dispersion experiments using advanced instruments, special experimental techniques and logistics were successfully carried out in an environment of large dimensions, strong stratification, and rapid currents flowing in opposite directions.

Both the dispersion computations, and the measurements indicate that the dye is rapidly diluted in the lower layer of the Bosphorus within a short distance (within few km) after the diffusers. This is especially true in the case of instantaneous dye releases, where dilutions of 10^{-5} to 10^{-6} are achieved in the lower layer until the dye reaches the northern end of Bosphorus. In the case of continuous discharge, which is more relevant for the waste

discharges, the only major component of dilution that is expected to occur (comparing the well mixed lower layer concentration with the injected concentration) is of order Q/Q_ℓ, and is entirely due to the redistribution of wastewater flux across the Bosphorus lower layer cross-section. Taking $Q = 2 - 6m^3/s$ for typical operating conditions of the Ahırkapı discharge, and $Q_\ell = 5000 - 15000m^3/s$ (Table 3.1) for the Bosphorus lower layer flux, we expect that the dilution ratio in the continuous discharge case will be on the order of 10^{-3} to 10^{-4} for the lower layer waters. In this case the average concentration does not change much along the Strait, because relatively small losses occur by decay and entrainment processes.

One of the most important results of the study is that it verifies that the assumptions used in the design of the wastewater disposal system of the City of İstanbul were basically correct. Those design concepts were based on the annual mean budgets of salinity, which is a conservative tracer itself, as discussed in Chapter 2. It is shown that the dye releases, and therefore the wastewater, behave in the same way as salinity, despite complicating factors of wastewater buoyancy, source location and other three-dimensional effects.

Some of the dye injected in the lower layer mixes into the interfacial layer and is trapped there, while a still smaller fraction finds its way to the surface. Whatever amount reaches the upper layer cannot be established precisely because it is a small concentration on the same order as the background levels.

Extreme cases of lower and upper layer blocking were sampled during the March and December 1993 experiments. Either case did not lead to critically different 4esults as compared to normal conditions, with regard to dye entrainment into the upper layer.

In March, 1993, the lower layer flow was very low (close to being blocked) when the dye was introduced, but the dye was confined in this layer for a long period without being mixed up by a significant amount into the upper layer, and slowly flowed across the northern sill into the Black Sea.

In December 1993, the entire Bosphorus waters flowed towards the north, retaining the two layer density stratification of Marmara waters advected north in both the upper and the lower layers. Despite the effective blocking of the true upper layer (Black Sea) waters at the northern entrance, the stratification between the two layers originating from Marmara persisted, and prevented contamination of the surface waters. The lower layer dye patch moved north at a fast rate.

Following the dye releases, the average upper layer concentrations in the Bosphorus were always less than about 0.4 *ppb*; the interfacial layer concentrations were always less than 1.6 *ppb* in all of the experiments; while the highest mean concentrations observed in the lower layer waters was up to about 80 *ppb*.

Outside the Bosphorus, there were background concentrations of up to 3 *ppb* in the surface layer of the Marmara exit region. Therefore, the effects of dye release could not be established there. But, based on other indications, very little dye reached the surface in any of the experiments, including those with extreme and adverse conditions. Comparison with simple models of dispersion showed good agreement for the lower layer transports in the Bosphorus.

The simultaneous measurements of current velocity and Rhodamine-B dye at some sections allowed the calculation of dye fluxes across the Bosphorus, during the August 1992 and March 1993 experiment. Based on flux monitoring at a fixed cross-section, about 20 - 60 % of the total mass injected is recovered along the Bosphorus. Given the uncertainties, this is quite an important result, showing the level of reliability of the experiments.

CHAPTER 6

BIOCHEMICAL TRACERS

6.1 Methodology

Sea water fluoresces by virtue of the dissolved organic compounds it contains which possess structures, such as aromatic rings, having systems of delocalised electrons. Such compounds include proteins, aromatic aminoacids, flavins, chlorophyll, fulvic and humic acids and polynuclear aromatic hydrocarbons. These compounds are readily detected even if present only in trace quantities and fluorescence spestroscopy may therefore be used to distinguish natural waters though only a limited amount of work has been published on this subject. Since fluorescence arises from dissolved organic compounds (including compounds present in tiny particles such as phytoplankton cells), measurements of fluorescence give direct information on dissolved organic matter in sea water. A major component of the Ahırkapı waste water consists of soluble and readily suspendable organic matter which could be investigated with the same methods.

Four cruises by R/V BİLİM (in August and December, 1991, March, 1992, and May, 1992) have investigated the natural fluorescence of the Bosphorus. Each cruise occupied several days and permitted a sytematic investigation of the Bosphorus. On the three cruises the fluorescence of the underflow was studied both when Ahırkapı waste water was being discharged (a so called "positive pulse" experiment) and also when the discharge was switched off (a "negative pulse" experiment). The data obtained during the cruises in 1991 were reported in Latif *et al.*(1992).

All fluorescence measurements were made in the laboratory by a Hitachi F3000 spectrofluorometer on samples of water taken systematically by R/V BİLİM from known locations and depths in the Bosphorus. The following procedure was devised in order to characterise the fluorescence of the organic material in the Bosphorus waters: The Excitation (230-430nm, Emission wavelength 440nm), Emission (240-450nm, Excitation wavelength 230nm) and Synchronous (from 220-600nm, constant wavelength difference 50nm) spectra of each water sample were recorded. The spectra were uncorrected but, in order that the spectra from different water samples could be compared quantitatively, the heights of all significant peaks were measured with respect to the height of a nearby peak due to the Raman scattering of water. The intensities of Excitation maxima at 230 and near 330nm

were measured relative to the height of the Raman scattering close to $380nm$. The intensities of Emission maxima near 400, 345 and $300nm$ were measured relative to the height of the Raman scattering close to $254nm$. The intensities of synchronous maxima at 230 and $280nm$ were measured relative to the Raman scattering close to $354nm$. For each water sample, these seven major relative fluorescence intensities were summed to give an arbitrary measure of the total fluorescence, TF, of the sample.

Since the faecal coliform bacteria (FC) are the inevitable component of untreated domestic sewage, their concentration, stated as the number of FC/100 ml sample, is one of the simplest and direct method of monitoring the behaviour of a waste plume in the Bosphorus underflow. This is the main reason for monitoring the variations in concentrations of FC along the Bosphorus and within its junctions with the Black Sea and the Marmara Sea since 1985 within the framework of the İSKİ–Ahırkapı Discharge Project. The results of yearly expeditions were compiled and presented to İSKİ as Progress and Annual Reports. Here is presented the distributions of FC and halocarbons along the Bosphorus and its junctions under different flow conditions, *i.e.* blockages of upper and lower layer flows, diversion of the Ahırkapı deep–sea discharge to the surface layer of the Bosphorus Marmara junction region.

Four experiments were conducted during the 1991-1993 period for tracing the waste plume and determining the extent and magnitude of advection and turbulent mixing along the Bosphorus. Three of them were the positive and negative discharge type experiments. In the former experiment the Ahırkapı Sewage outfall was in full operation whereas in the latter case sewage pumping into the lower layer was stopped and discharged to Marmara surface waters. The dates and the types of experiments conducted at different periods together with the volume fluxes of upper and lower layers of Bosphorus measured by ADCP (Acoustic Doopler Current Profiler) are summarized in Table 6.5.

During these positive-negative discharge experiments, two lower layer blockage events were recorded. The first one was during the 8–10/03/1992 period and the second was during 14–15/05/1992 period. During March,1992 experiment the lower layer flow of Bosphorus was bloked due to the strong norhteasterly winds while the Ahırkapı diffuser was fully operating, *i.e.*, positive discharge experiment. On the other hand, during the May,1992 experiment the diffuser was not operating, *i.e.* negative discharge. Although positive-negative discharge type experiment was not planned, the chance of measuring the FC levels under positive discharge but upper layer blockage conditions (ULB) was obtained during December, 1993 expedition due to the strong southwesterly winds (Lodos).

In order to make the discussions clear and simple, variations at some stations located at the dynamically and topographically critical positions of the Bosphorus are selected. Station B0 is positioned on top of the Ahırkapı diffuser, E2 is located to the south of diffuser on the Marmara side; stations B5, B7 and B8 are located at the narrowest, control section

of the strait where hydraulic jump occurs, and stations B14 and B15 which are located at the northern exit of the strait.

6.2 Natural and Waste water Fluorescence Characteristics of the Bosphorus

As reported previously by Latif *et al.*(1992), in examining sea water samples from stations 45C in the Sea of Marmara to K0 in the Black Sea for their fluorescence characteristics it appears sufficient to note that one is sampling a two layer system in which the pycnocline becomes deeper from south to north and the surface density increases from north to south. The one major and interesting exception occurs when the Bosphorus is blocked. The details of the physical oceanography are discussed in Chapter 3, and the results obtained from the fluorescence measurements will be discussed together with the physical parameters.

Despite the variations from one cruise to another, the upper Black Sea water can be readily distinguished from the Mediterranean underflow water throughout the year, based on the total fluorescence intensities and the ratios of the relative fluorescence observed in the synchronous and emission spectra. This is shown in Table 6.1, where the seven major relative fluorescence intensities and the total fluorescence described above are recorded. If it may be assumed that the total fluorescence, as it has been defined here, is directly proportional to the concentration of dissolved organic material, then Table 6.1 shows the Black Sea water to carry at least twice the concentration of dissolved organics as the Mediterranean counterflow. Direct measurements of the dissolved organic material suggest a slightly higher value for this ratio. Table 6.1 also suggests the proportions of compounds having excitation wavelengths near $280nm$ and which, when excited by light having a wavelength of $230nm$, fluoresced near $345nm$, to be diminished in the Mediterranean underflow. This would be consistent with a relative absence in Mediterranean water of compounds, such as tryptophan, having structures containing certain substituted benzene rings.

Each sample of Ahırkapı waste water which has been analysed has differed in composition and concentration. Nevertheless, all samples have given synchronous, excitation and emission fluorescence spectra very similar to those of Mediterranean sea water. In consequence, Ahırkapı waste water cannot be distinguished quantitatively from Mediterranean sea water at concentrations smaller than that obtained by a dilution of 1/100 or greater. On the other hand, it is probable that, once it has escaped from the vicinity of the discharge, the flow of Ahırkapı waste through the Bosphorus will be entirely similar to the flow of soluble, fluorescent, organic material in general. Table 6.2 compares the total fluorescence of the Bosphorus underflow in the presence and absence of discharged waste (positive and negative pulse experiments).

It is clear that, if the total fluorescence may be assumed to be directly proportional to the concentration of dissolved organic material, then the discharge of Ahırkapı waste never

amounted to more than 10% of the organic material dissolved in the lower layer of the Bosphorus and may well be much less. The negative and positive pulse experiments in March and May 1992 were separated by a period of a few days when the Bosphorus was blocked and one might expect there to have been 'natural' differences in the fluorescence of the underlayer over such a period. The concentration of dissolved organic matter in the upper layer being at least twice that in the Mediterranean water, even if all the Ahırkapı waste became transferred to the upper layer, it would make no significant difference to its fluorescence and it is not surprising that the total fluorescence of Black Sea water remains unaltered in negative and positive pulse experiments. One may further point out that comparison of the total fluorescences given in Tables 6.1 and 6.2 indicates that the variations in the concentrations of dissolved organic material introduced into the Sea of Marmara by the Black Sea current greatly exceed the concentration of soluble waste discharged from Ahırkapı .

In all cruises, the patterns of fluorescence characteristic of the Black Sea and the Mediterranean waters (Table 6.1) were readily traced as they flowed through the Bosphorus and into the Sea of Marmara and the Black Sea respectively. Changes in the fluorescence characteristics were generally attributable to mixing of the two flows. Accordingly, as one journeys from north to south through the Bosphorus the density of the surface water increases and its fluorescence decreases, consistent with increasing mixing of the lower layer (higher density, lower fluorescence) into the upper layer. This is illustrated by the total fluorescence measured in December 1991 and shown in Table 6.3.

The most obvious fact shown by the natural fluorescence data (Table 6.4) is the relatively high intensity of fluorescence shown by the upper layer of Black Sea water and the consequent marked change in fluorescence that occurs across the pycnocline. Closer inspection of the depth profiles reveals that the total fluorescence is exceptionally high near the surface, just below or in the pycnocline and, occasionally, in a layer near the sea bed. The fluorescence near the surface is intense because (a) this is where one finds Black Sea water and (b) there appear to be localised inputs of fluorescent organic material into the surface waters (The study of Faecal Coliform - Section 6.2 shows these inputs to include waste material).

On several occasions, during the cruises of March and May, 1992, the lower layer flow of the Bosphorus was blocked (Chapter 3), which served as an opportunity to investigate the chemical oceanography of the Strait under these comparatively unusual conditions. The results of the analyses are given in Table 6.4.

Table 6.4 shows that, during the blockage on 8 March, the Bosphorus water possessed (a) unusually low values of σ_t (that is, it was occupied by the brackish waters of the Black Sea), (b) slightly high values of dissolved oxygen, and (c) slightly low concentrations of nutrients. Moreover, throughout the March cruise, and especially whilst the Bosphorus was

blocked, the values of total fluorescence were particularly high. Thus, during the March blockage, the Black Sea water entering the Bosphorus was well aerated, perhaps because of unusual weather conditions in the Black Sea itself; that the nutrient concentration of the water entering the Marmara was low, together with the high values observed for the total fluorescence suggests that the inflowing water was exceptionally fertile.

The partial blockage observed in May 1992 was very similar to the March 1992 blockage. All the analyses (Table 6.4) are consistent with the downward extension of an upper layer of less dense, highly fluorescent water, lacking in nutrients.

6.3 Faecal Coliform Measurements

Results of FC measurements at selected stations under different environmental and experimental conditions are given in Tables 6.6 - 6.9 for the periods given in Table 6.5. In addition, FC measurements made during the Rhodamine-B dye release experiments of August - September 1992 are given in Table 5.1, which can be used to locate FC maxima relative to the dye dispersion patterns. FC data for the Stations B14 and B15 are seperately given in Table 6.10 because they represent the far-field. region for the waste plume.

FC concentrations measured within the lower layer of Bosphorus rapidly diminish to levels of less than 50 FC/100 ml, when the deep-sea waste discharge is diverted to surface waters of the Marmara Sea at the exit of the Bosphorus, *i.e.*, negative pulse. The decrease after the negative pulse suggests that the FC levels measured within the lower layer of Bosphorus originates only from the deep-sea discharge. In other words, waste discharges into the upper layer from other sources have little effect on the FC content of the lower layer of the Bosphorus. During the same period, *i.e.*, negative discharge, the FC content of the upper layer of the Bosphorus, except those located in the BMJ region, remained practically unchanged in comparison to the levels recorded previously, indicating that the upper layer concentrations are not related in any way to wastes discharged through the the Ahırkapı diffusers (Station E2, Tables 6.6 and 6.7).

When the diffuser is in operation and the lower layer flow is blocked (LLB) which was observed during 08/03/1992 (Table 6.7) and 14-15/05/1992 (Table 6.8) periods, FC levels of Stations E2 and B0 are slightly affected down to 35-40 m which are well within the lower layer water of Marmara Sea.

Unlike the lower layer, FC concentrations in the upper layer were unchanged by positive or negative pulse; the FC in the upper layer arosed from localised discharges. The only detectable changes in the FC levels of upper layer of Bosphorus are observed when the upper layer flow is blocked (ULB). This special condition was observed during the December, 1993 experiment. Under the ULB conditions FC levels of the upper layer increased at all

stations (Table 6.9) compared to other cases. For example, at Station B8, upper layer FC concentration varies between 20-100 FC/100 ml under normal upper and lower layer flow conditions, during positive or negative type discharge experiments and even during LLB events (Tables 6.7 and 6.8). However, under conditions of upper layer blockage (ULB), as was observed in December, 1993 (Table 6.9), FC in the upper layer waters of all stations extending from the southern exit to northern exit (Table 6.10) increased to levels of more than 500 FC/100 ml. When one examines the FC levels of the upper layer waters at Stations B14 and B15 (Table 6.9, Dec.,1991; March,1992 and May,1992 periods) it is seen that its concentration is always zero under other conditions. It can be stated that the sewage field originating from the Ahırkapı discharge is not effecting the surface waters of the region north of Stations B5–B7 except under the upper layer blockage conditions induced by strong southwesterly winds, when the heavily polluted Marmara upper layer waters back up into the Bosphorus.

6.4 Low Molecular Weight Halocarbons

Of the various halocarbons (HC) studied, HC distribution in the Bosphorus Strait exhibit different vertical features depending on their sources; and they can be separated into three groups. The first group consists of the anthropogenic, airborne chlorofluorocarbons $CFC-11$, $CFC-113$. The second group, chloroform and dibromomethane, show similar patterns even if it is doubtful that their sources are the same. The third group is represented by methyl iodide and chloro-iodomethane, both of which are generally believed to be of exclusively biogenic origin.

6.4.1 Chlorofluorocarbons

Displayed in the Figure 6.1 are the longitudinal transects of the chlorofluorocarbons, shortly $CFC-11$, $CFC-113$ and CCl_4. The three figures have certain similarities; low concentrations in the inflowing Mediterranean water, the highest values in the intermediate layer at the entrance to the Black Sea and a slight influence of CFC-113 only from the İstanbul area. The lowest concentrations of chlorofluorocarbons, *i.e.* the "oldest" water mass, was found in the deep water (salinity > 38) at station E5 located at the southern exit of the Bosphorus. In surface water of 14 ° C and a salinity of 38, the concentrations measured were those of an equilibrium with the atmosphere in about 1981–1983 (Warner and Weiss, 1986). The ratio of 16.5 ($CFC-11/CFC--113$) indicates that the deep water, when entering the Bosphorus from the Marmara Sea, was at the surface in the Mediterranean Sea in 1984. An estimation of 8–11 years is reasonable as the residence time of the deep water in the Marmara Sea since the $CFC-113$ values used in this calculation are close to the detection limits.

6.4.2 Chloroform and dibromomethane

Distributions of chloroform and dibromomethane are shown in Figure 6.2. These two compounds differ from the chlorofluorocarbons (Figure 6.1) in the sense that there is a pronounced source in surface water in the vicinity of İstanbul.

A striking feature in the distribution of chloroform (Figure 6.2a) is that the highest concentrations were found in the upper layer at the Marmara exit of the Bosphorus. Keeping in mind that the surface currents in the area are southbound, it seems reasonable to draw a conclusion that the source for these high levels are the domestic and industrial effluents from the İstanbul area. There is also a diffuse source of chloroform in the surface layer, possibly resulting from dispersed surface discharges of effluents from the communities along the strait. However, recent reports on the biogenic production of chloroform by algae, and the exceptionally high primary production in the area does not exclude natural production.

Dibromomethane shows a similar distribution pattern (Figure 6.2b) as chloroform does. However, it is likely that the sources are not the same. There seems to be a point source for dibromo–methane at about 15–20 m depth at Stations D2 and C2 on the Marmara side. This could be related to an algal bloom in the water, and need not be an anthropogenic input. It has been shown that the region is highly enriched in dissolved nutrients due to domestic wastes and entrainment of nutrient rich water from the lower to the upper layer of the Bosphorus (Bastürk *et al.*, 1986) due to the entrainment induced in the strait. Thus, the region has higher algal production and chlorophyll-a concentrations than other regions of the Marmara Sea and the southwestern Black Sea. Wherever the sources for chloroform and dibromomethane are to be found, they follow the same spreading pattern along the strait. The point sources are within the pycnocline and there is an isopycnal distribution along the interface between the surface Black Sea water and underlying Mediterranean water.

The collective hydrocarbon data versus depth, plotted in Figure 6.3, show elevated concentrations in the 10-20 m depth interval as noted earlier. To characterize the distribution relative to the different water masses, the collective hydrocarbon concentration data are plotted against salinity in Figure 6.4, showing that a large number of data with low concentrations fall either within the upper layer (salinity < 19) or the lower layer (salinity $>$ 37) waters, while the rest of the data with relatively higher concentrations fall within the interfacial layer between the upper and lower layers (salinity > 17 and < 37), corresponding to a thickness of only about 10 m. We therefore suggest that the high concentrations of hydrocarbons observed along the interfacial layer in the southern Bosphorus and in the Marmara Sea region could result from sources other than the Ahırkapı waste discharge. Sources for this concentration maximum could be the surface discharges in the region, *e.g. the Golden Horn*, or the shallow parts of the Marmara exit, where pollutants can be

accumulated at the interface in stillwater conditions, later to spread into the surrounding Bosphorus waters at the exit region.

There is only a week signal of chloroform in the İstanbul sewage water coming out of the diffusers due to the fact that no chlorination of the sewage was taking place at the time for the investigation. However even this weak signal seems to be important in the lower layer.

Chloroform concentrations measured in the original waste water taken from the Ahırkapı pump station have been reported by Latif *et al.*(1992). The average concentration of chloroform in the original waste was 1900 $ng/l\ CHCl_3$. With an expected initial dilution of about 1/50 by the diffusers, the concentration at exit to the Bosphorus lower layer waters would be on the order of 40 $ng/l\ CHCl_3$. Our sampling seems to have missed the dye patch near the source since the concentrations for the lower layer at Station B0 are much lower. The dilution along the lower layer flow of the Bosphorus due to dispersion effects is expected to be very rapid and analogous to the dispersion of Rhodamine-B. The total dilution of waste along the length of the Bosphorus, calculated for a continuous release experiment (Chapter 5) was found to be on the order of 5×10^{-4} in the case of Rhodamine-B. Discounting the adsorption and decay losses which we assume would not be valid for hydrocarbons the dilution would be on the order of 10^{-3} or larger within the Bosphorus, yielding concentration increases of 2 $ng/l\ CHCl_3$ or greater in the lower layer resulting from the waste discharges. We do see such increases of concentration along the length of Bosphorus when we consider the lower layer data alone. Plotting the hydrocatbon concentration for data points with salinity > 37, Figure 6.5 shows an increase of hydrocarbons north of station B0. This increase appears to be related to the Ahırkapı waste water discharge and is of the same order of magnitude as would be expected from dispersion in the lower layer.

6.4.3. Methyl iodide and chloro-iodomethane

Two iodinated compounds, methyl iodide and chloro-iodomethane were identified during the study. Their distributions in the Bosphorus shown in Figure 6.6 have very similar distribution patterns. Elevated concentrations of both compounds were measured in the upper 10–15 m all along the Bosphorus. (0.65–0.70 ng/L CH3I and 0.30–0.49 ng/L CH2ClI) The highest concentrations (0.90 ng/L for CH3I and 0.93 ng/L for CH2ClI) were detected in the upper layer of the BMJ region where there was also a considerable source of chloroform and dibromomethane as mentioned above. However, the iodinated halocarbons do not follow the same pattern of an isopycnal plume as do chloroform and dibromomethane. Iodinated compounds appear to have sources close to the surface. The nearly homogeneous distribution of the iodinated compounds in the upper layer all along the strait north of the station B0 indicates that they emanate from diffuse, probably biogenic, sources within the

upper layer of the strait and/or the Black Sea. Additional inputs by pelagic algal production in the BMJ region, which was shown to support the highest planktonic production as compared with the offshore waters of the Marmara Sea (Baştürk, *et al.*, 1986; Göçmen, 1988), makes this region contain high levels of iodinated halocarbons.

Methyl iodide and chloro-iodomethane concentrations were also relatively high in the deep water of stations B15 and K3 compared with the inflowing Marmara Sea deep water.This relative increase in deep water implies another, and probably benthic, production on the slopes of the Bosphorus close to the exit to the Black Sea.

6.5 Conclusions

Fluorescence measurements readily distinguish the flows of Black Sea and Mediterranean water through the Bosphorus by the difference in their contents of dissolved organic material. However, it is not possible to distinguish the Ahırkapı discharge in this way. It is shown that the major flux of dissolved organic material into the Marmara Sea was the flow of Black Sea water through the Bosphorus. The soluble organic material from the Ahırkapı discharge was never observed to exceed 10% of the total concentration in the lower layer of Mediterranean water. The concentration of dissolved organic material increased by some some 10% when the lower layer flow of the Bosphorus was blocked.

The highest concentrations of fluorescent material were found near the surface of the Bosphorus, just below or in the pycnocline, and, less generally, in a layer near the sea bed.

Faecal coliform analyses have shown that, within the Bosphorus lower layer flow arises solely from the Ahırkapı discharge and their concentrations extend through the lower layer, far into the Black Sea.

It is difficult to estimate the fraction of the FC injected into the upper layer from the lower layer, since already high concentrations exist in the upper layer as a result of localized discharges of waste water within the surface layer.

In addition to the traditional halogenated transient tracers ($CFC-11$, $CFC-113$, CCl_4) the halocarbons $CHCI_3$, CH_2Br_2, CH_3I and CH_2ClI were used for the characterisation of water masses in the Bosphorus Strait. Even if the last four halocarbons have source functions that are less known, they can be utilised for complementary information concerning movement and mixing of water masses.

Elevated concentrations of $CHCI_3$, CH_2Br_2, CH_3I and CH_2ClI in the Bosphorus Marmara Junction (BMJ) can be attributed to anthropogenic inputs, but contributions from biological production, which is high in the area, must also be considered.

Halocarbon measurements imply that the region around the Marmara exit of the Bosphorus are affected by waste waters discharged into the sea from surface sources. Since the surface layer of water mass in the region is in equilibrium with atmospheer upper ponts of the upper layer loses its HC rapidly, resulting in the hydrocarbon accumulation within the interfacial layer at depths of 10-20m. The HC distributions indicate that high concentrations primarily occurs in the Marmara Sea region and partially extends into the Bosphorus.

CHAPTER 7

CONCLUSIONS

The Bosphorus constitutes a unique two-layer flow system with a wide range of variability in its regimes, on a seasonal, interannual and day-to-day basis. It is often the average behaviour (*e.g.* the mean annual fluxes, salinity budgets) that, in the past, has concerned scientists and managers alike. However, we now know that the short-term variability and its consequences on the environment are just as important as the mean seasonal behaviour, and significantly influences the latter, as it is typical of nonlinear systems, of which the Bosphorus is a good example.

The lower layer currents are stable in direction (mostly to the north, occasionally stopping or reversing to the south), and variable in magnitude. Stopping of the flow, or complete current reversals (with a saline wedge propagating south) often takes place. In a similar manner, the upper layer flow becomes blocked, under southwesterly winds, leading to short term increases in surface salinity (Orkoz) in the Bosphorus. Many cases of blockage events have been observed, and the statistical information on their occurrence have been gathered.

Sea level measurements were strongly correlated with the Bosphorus currents and blockage.

The volume fluxes exchanged between the adjoining seas have been calculated based on ADCP measurements. The average upper layer fluxes were found to be of the same order as the average fluxes computed from mass balances. On the other hand, the lower layer fluxes were found to be lower than most budget estimates. The most significant result of these measurements is the variability of the flows, showing that the transient Bosphorus fluxes change over a wide range of values, which can differ significantly even within a single day.

A review and comparison of nutrient and carbon fuxes through the Bosphorus shows that the Marmara Sea is dominated by the influence of the Black Sea. The load from the City of İstanbul metropolitan area appears to be only a fraction of the load that comes in from the Black Sea. Part of the load is exported back to the Black Sea and to the Aegean Sea.

The wastewater discharged from the Ahırkapı diffusers forms a buoyant plume in an environment of two-layer stratification and currents in the Bosphorus. For quantitative assessments of the plume system, the ADCP system (150 KHz transducers), and the 30 KHz

transducer of the JMC echosounder on board the R/V BİLİM were used for quantitative and qualitative measurements of backscatter from suspended particulates in the plume.

Due to the high levels of particulate material in the discharge, a well defined plume structure could be observed during the surveys. The fast lower layer currents were observed to bend the plume northward, forcing it to move parallel to the bottom. Other observations showed the plume arrested at the pynocline level.

Instantaneous and continuous dye release experiments were performed in the Bosphorus and adjoining exit regions. Two oceanographic ships were equipped with in-situ fluorometers interfaced to CTD and rosette systems were used, and a special sampling strategy was developed for the Bosphorus, gathering four-dimensional data on the dye dispersion, which allowed calculations of fluxes and total transports, as well as comparisons with estimates based on semi-empirical theory.

Based on dispersion computations, the maximum concentration of an instantaneous discharge was established to decrease rapidly by some orders of magnitude in the southern Bosphorus. The maximum concentration decreases further bay a factor < 10 when the dye patch reaches the northern end of the Bosphorus, about a day after its introduction at the diffuser. It was found that vertical and transverse mixing could only be achieved partially near the northern end of the Strait. The maximum dilution for instantaneous releases is on the order of 10^{-5} to 10^{-6}.

In the case of the continuous pulse dye release, dilution occurs entirely due to the redistribution of wastewater flux across the Bosphorus lower layer cross-section. The maximum dilution for continuous release is on the order of 10^{-3} to 10^{-4}.

Extreme cases were sampled during the March and December 1993 experiments. In March, the lower layer flow was very low (close to being blocked) when the dye was introduced, but the dye was confined in this layer for a long period without being mixed up by a significant amount into the upper layer.

In December 1993 the entire Bosphorus waters flowed to the north, retaining the two layer density stratification of Marmara waters advected north. Despite the effective blocking of the true upper layer (Black Sea) waters at the northern entrance the stratification between the two layers originating from Marmara persisted, and prevented contamination of the surface waters. The lower layer dye patch rapidly moved north.

Following the dye releases, the observed average upper layer concentrations in the Bosphorus were always less than about 0.4 *ppb*; the interfacial layer concentrations were always less than 1.6 *ppb* in all of the experiments; while the highest mean concentrations observed in the lower layer waters was up to about 80 *ppb*.

Outside the Bosphorus, there were background concentrations of up to 3 *ppb* in the Marmara exit region. Therefore the effects of dye release could not be established there. But, based on other indications, very little dye reached the surface in any of the experiments. Comparison with simple models of dispersion showed good agreement for the lower layer transports in the Bosphorus.

The simultaneous measurements of current velocity and Rhodamine-B dye at some sections allowed the calculation of dye fluxes across the Bosphorus, and the computed total transports verified the success of measurements, within the level of accuracy of the measurements and the assumptions that had to be made.

One of the most important results of the study is that it verifies that the assumptions used in the design of the wastewater disposal system of the City of İstanbul were basically correct. It is shown that in the cross-sectional averages, the wastewater behaves in the same way as salinity, despite complicating factors of wastewater buoyancy, source location and other three-dimensional effects. Based on flux monitoring at a fixed cross-section, about 20 - 60 % of the total mass injected is recovered along the Bosphorus.

Fluorescence measurements readily distinguish the flows of Black Sea and Mediterranean water through the Bosphorus by the difference in their contents of dissolved organic material. However, it was not possible to distinguish the Ahırkapı discharge in this way. Measurements indicated that the major flux of dissolved organic material through the Bosphorus - and into the Marmara Sea - was the flow of Black Sea water. The soluble organic material from the Ahırkapı discharge was never observed to exceed 10% of the total concentration in the lower layer of Mediterranean water. The increase in the concentration of dissolved organic matter in the Bosphorus and flowing into the Sea of Marmara during the periods of blockage was of the order of some 10%.

Measurements of concentrations of Faecal Coliform are the most direct assessment of the unhealthiness of the Ahırkapı waste. Concentrations (dangerously) in excess of WHO recommendations continue to be found in both layers of the Bosphorus. It has been established that Faecal Coliform in the Bosphorus underlayer arises solely from the Ahırkapı discharge and, at least on occasion, concentrations of the bacteria extend through the lower layer and into the Black Sea as far as station K3 (at 60-70 *m* depth). The reasons for the comparatively long life of the bacteria in the lower layer cannot yet be explained. Bacteria also exist in the upper layer, but their presence is linked to local surface discharges, rather than the Ahırkapı waste discharge.

Halocarbon measurements imply that the region around the Marmara exit of the Bosphorus is affected by waste waters discharged into the sea from surface sources near the center of the City of İstanbul. Since the surface layer of water mass in the region is in equilibrium with atmosphere, upper parts of the upper layer loses its halocarbon rapidly, resulting in

hydrocarbon accumulation within the interfacial layer at depths of 10-20 m. The halocarbon distributions indicate that this zone of high concentration primarily occurs in the Marmara Sea region and partially extends into the Bosphorus. On the other hand, an increase of halocarbon concentrations north of the Ahırkapı diffusers is evident in the lower layer, though the level of this increase is on the same order of magnitude as the background.

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APPENDIX 1

FREQUENTLY USED CONCENTRATION UNITS AND INSTRUMENT SENSITIVITY RANGES

$$10^3 cm^3 = 1l = 10^{-3} m^3$$

CONVERSION TABLE FOR CONCENTRATION UNITS

$$10^3 ng/l = 1\mu g/l = 10^{-3} g/m^3 = 10^{-6} kg/m^3 = 1ppb$$

$$10^{-3} ng/l = 10^3 \mu g/l = 1g/m^3 = 10^{-3} kg/m^3 = 1ppm$$

$$10^{-6} ng/l = 10^6 \mu g/l = 10^3 g/m^3 = 1kg/m^3 = 1ppt$$

MEASUREMENT RANGE OF CHELSEA INSTRUMENTS AQUATRACKA III FLUOROMETER

$$0.01\mu g/l - 100\mu g/l$$

$$0.01ppb - 0.1ppm$$

$$10ng/l - 10^5 ng/l$$

$$10^{-8} kg/m^3 - 10^{-4} kg/m^3$$