FLUORESCENT DYE MEASUREMENTS OF THE MIXING AND TRANSPORT OF WASTEWATER DISCHARGE IN THE BOSPHORUS

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ABSTRACT

The performance of the wastewater discharge of İstanbul is evaluated based on fluorescent dye technique, supported by hydrographic and current measurements. Under the normal exchange flows, as well as during extreme events of blocking, the dye essentially remained confined in the lower layer. The maximum upper layer average dye concentration in the Bosphorus was close to the background levels, while the interfacial layer values were larger. Good agreement is found between the observations and simple models of longitudinal dispersion in the lower layer of the Bosphorus.

KEYWORDS

Waste, diffuser, currents, fluorescence, dye, tracer, Bosphorus, strait.

INTRODUCTION

The design of the wastewater disposal system for İstanbul (DAMOC 1971, Gunnerson and Özturgut, 1974, Gunnerson, 1974) is based on the discharge of wastes into the Bosphorus lower layer flow, in a critical area of the Turkish Straits System (the Bosphorus, Dardanelles Straits and the Sea of Marmara), affected by pollution loads from local and external sources (Polat and Tuğrul, 1994).

The exchange flows through the Bosphorus Strait are variable in response to forcing on various time scales (Ünlüata *et al.*1990, Oğuz *et al.*, 1990, Özsoy *et al.*, 1990, Özsoy *et al.*, 1992). Lower layer blocking occurs in spring / summer during increased net freshwater influx into the Black Sea and northerly winds, while the upper layer blocking (*Orkoz*) occurs in autumn and winter in response to southwesterly winds.

EXPERIMENTAL DESIGN AND METHODOLOGY

Rhodamine-B dye introduced at the Ahırkapı diffuser discharge (station B0, Figure 1) is used for an assessment of mixing and dilution of wastes in the Bosphorus. Two ships were used in the dye tracing studies: the R/V BİLİM of the Institute of Marine Sciences, METU, and the R/V ARAR of the Institute of Marine Sciences and Geography, İstanbul University, both equipped with CTD systems (Seabird 911 Plus) and fluorometers (Chelsea Instruments Aquatracka III). The R/V BİLİM also had a vessel-mounted acoustic Doppler current profiler (ADCP), a GPS system for positioning, a light transmissometer and a rosette sampling system. On the R/V ARAR Nansen bottles were used. Dye flux calculations were made by integrating current velocity (ADCP) and CTD profiles matched in post-processing. Some independent, though less accurate, laboratory analyses of water samples confirmed the results of in-situ fluorometry.

Among the water quality parameters affecting Rhodamine fluorescence (*e.g.*Wilson,1968), the most serious effect in Bosphorus was the adsorption on suspended particles. The Langmüir formulation (*e.g.*Shaw, 1991) relates the dye loss c_δ to concentrations of particulates (c_s) and initial dye (c_o) by $c_\delta = A_o\alpha\ c_s\ c_o/(1+\alpha c_o)$, where α and A_o are constants. Laboratory experiments with İSKİ wastewater showed a high adsorptive loss ratio of $(c_\delta/c_o) = 0.4 - 0.75$, but can be larger due to the variability in wastewater properties.

The interference of other organics in sea water can affect the measurement of Rhodamine-B dye fluorescence. Levels of $\pm 0.1 ppb$ in the Bosphorus survived a two-staged background correction scheme (Özsoy *et al.*, 1994), and larger backgrounds (about 0.3-3 ppb) remained in the Sea of Marmara, invalidating the measurements obtained there.

A summary of dye release experiments are presented in the following:

Dates of Experiment	Dye Release	Mass of Pure Rh-B kg	Calculated Adsorption D_a	Assumed Adsorption D_a	Number of Stations
28 - 31 Aug. 1992	Instantaneous	180	1.2±1.2	0.50	171
1 - 2 Sep. 1992	Continuous	408	(?)	0.50	96
3 - 7 Mar. 1993	Instantaneous	312	0.9±0.7	0.50	234
16 - 19 Dec. 1993	Instantaneous	312	0.2±0.1	0.25	83

The adsorption ratio $D_a \equiv 1 - (c_\delta/c_o)$ estimated from concentration measurements in the pre-treatment tank had large uncertainties, and values were assumed as shown. Diffuser dilution was taken as $D_d = 0.02$.

In the analyses of the dye distribution subsequent to injection we made use of the two layer stratification of the Bosphorus. The average concentrations $\bar{c}_1$, $\bar{c}_2$, and $\bar{c}_3$ respectively in the upper, interfacial and lower layers were computed in reference to locally defined salinity limits (Özsoy *et al.*, 1994).

A simple one dimensional model of the the average lower layer dye concentration was used in making dispersion calculations:

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

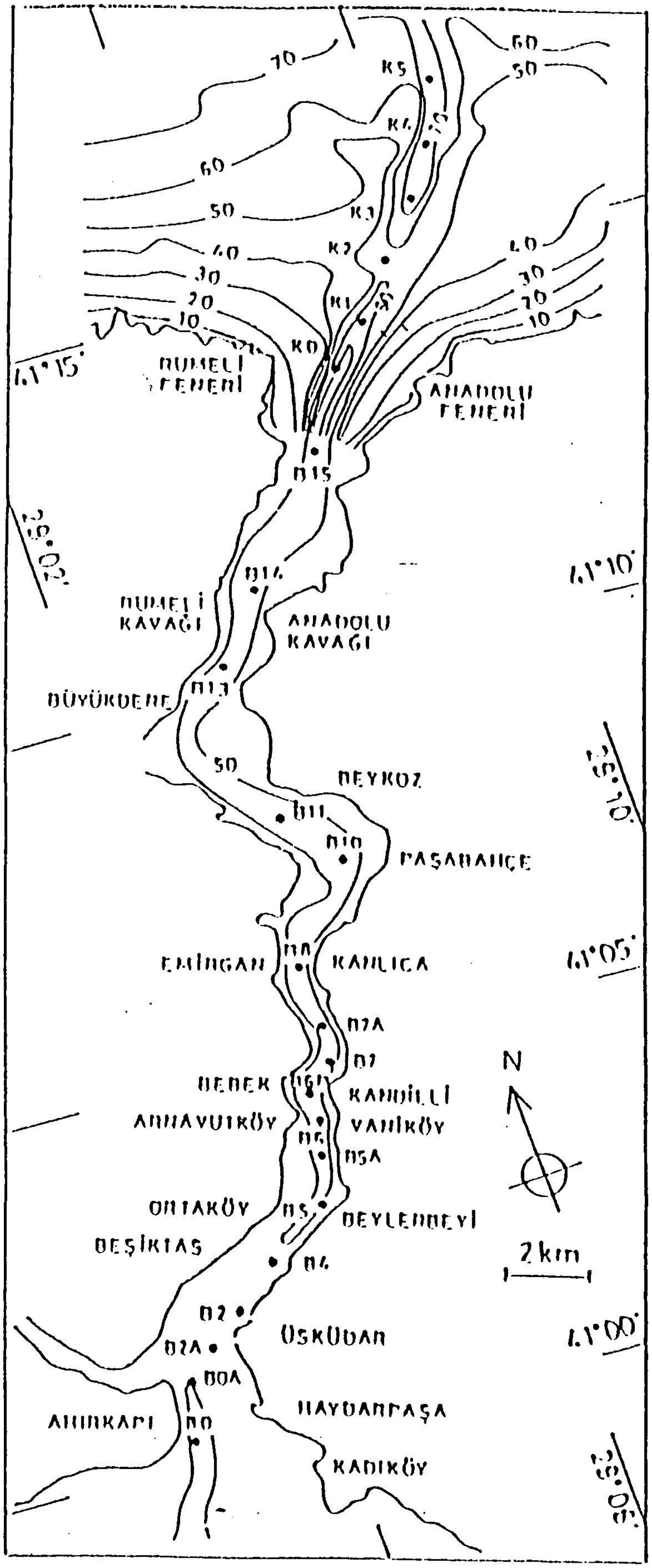

Figure 1. Regional map showing station positions, together with the bathymetry of the Bosphorus strait and its exits to Black Sea and the Marmara Sea.

which is similar the two-layer model of Thacker (1976), except that the lower layer has been decoupled by assuming that the vertical mixing term K_d is small, and the concentration difference between the layers is large. Although photochemical decay is negligible in the lower layer of the Bosphorus, a decay coefficient $K_d = ln(2)/T_d$ was necessary to account for post-injection adsorption and entrainment effects. An arbitrary value corresponding to a half-life $T_d = 24h$) was used in our calculations.

RESULTS

The dispersion coefficient and time scales in the longitudinal, transverse and vertical (x, y, z) directions respectively are estimated from the semi-empirical theory of estuarine mixing (Fischer *et al.*, 1979; and Smith, 1986):

$$E_x \equiv 0.01\frac{\bar{u}_\ell \bar{w}^2}{\bar{h}u_*} = 170\ m^2/s, \qquad T_x \equiv \frac{L_b^2}{E_x} = 60\ d,$$

$$E_y \equiv 0.15\bar{h}u_* = 0.14\ m^2/s, \qquad T_y \equiv 16\frac{\bar{w}^2}{\bar{h}\bar{u}_\ell} = 9\ h,$$

$$E_z \equiv 0.067\bar{h}u_* = 0.06\ m^2/s, \qquad T_z \equiv \frac{\bar{h}}{2\kappa u_*} = 5\ min,$$

where the estimates are given for typical values substituted for length L_b, mean depth $\bar{h} = h_\ell/2$, mean width $\bar{w} = w_\ell/2$ (triangular cross section) and average lower layer current speed $\bar{u}_\ell$. κ is the Von Karman constant, and u_* is the friction velocity $u_* \equiv \bar{u}_\ell(f/8)^{1/2}$, with f defined as the Darcy-Weisbach channel friction factor.

The vertical mixing is very fast, but transverse mixing is not expected to develop before the dye patch leaves the Bosphorus. The estimate for the longitudinal mixing coefficient is comparable to other estuarine regions of the world (Fischer *et al.*, 1979). Independent estimates based on the data yielded similar values of $E_x = 150 - 400 m^2/s$ (Özsoy *et al.*, 1994).

The maximum concentration near the source (measured c_d near station B0) is compared with its estimated value $c_d = D_a D_d c_i$, where c_i is the initial concentration in the injection tank. The measured average lower layer concentration $\bar{c}_{3,o}$ at the source is compared with the calculated average initial concentration $\bar{c}_{3,o} = c_i D_a Q/Q_\ell$, where Q/Q_ℓ is the ratio of the pipeline discharge to the estimated Bosphorus lower layer discharge. In addition, the maximum values of layer average concentrations in the Bosphorus are also listed:

Date	dye exp.	waste water flux Q (m^3/s)	l. layer Bosphorus flux Q_ℓ (m^3/s)	calc. diff. conc. c_d (ppb)	meas. diff. conc. c_d (ppb)	calc. source conc. $\bar{c}_{3,o}$ (ppb)	meas. source conc. $\bar{c}_{3,o}$ (ppb)	max. u.l. conc. $\bar{c}_{1,max}$ (ppb)	max. i.l. conc. $\bar{c}_{2,max}$ (ppb)	max. l.l. conc. $\bar{c}_{3,max}$ (ppb)
Aug. 1992	Inst.	2	7500	2000	80	54	52	0.16	0.63	52.3
Sep. 1992	Cont.	2	12000	17	10	1	4	0.29	0.41	3.8
Mar. 1993	Inst.	6	5000	1300	64	31	21	0.18	0.92	21.0
Dec. 1993	Inst.	2	19000	1700	108	36	79	0.38	1.56	78.9

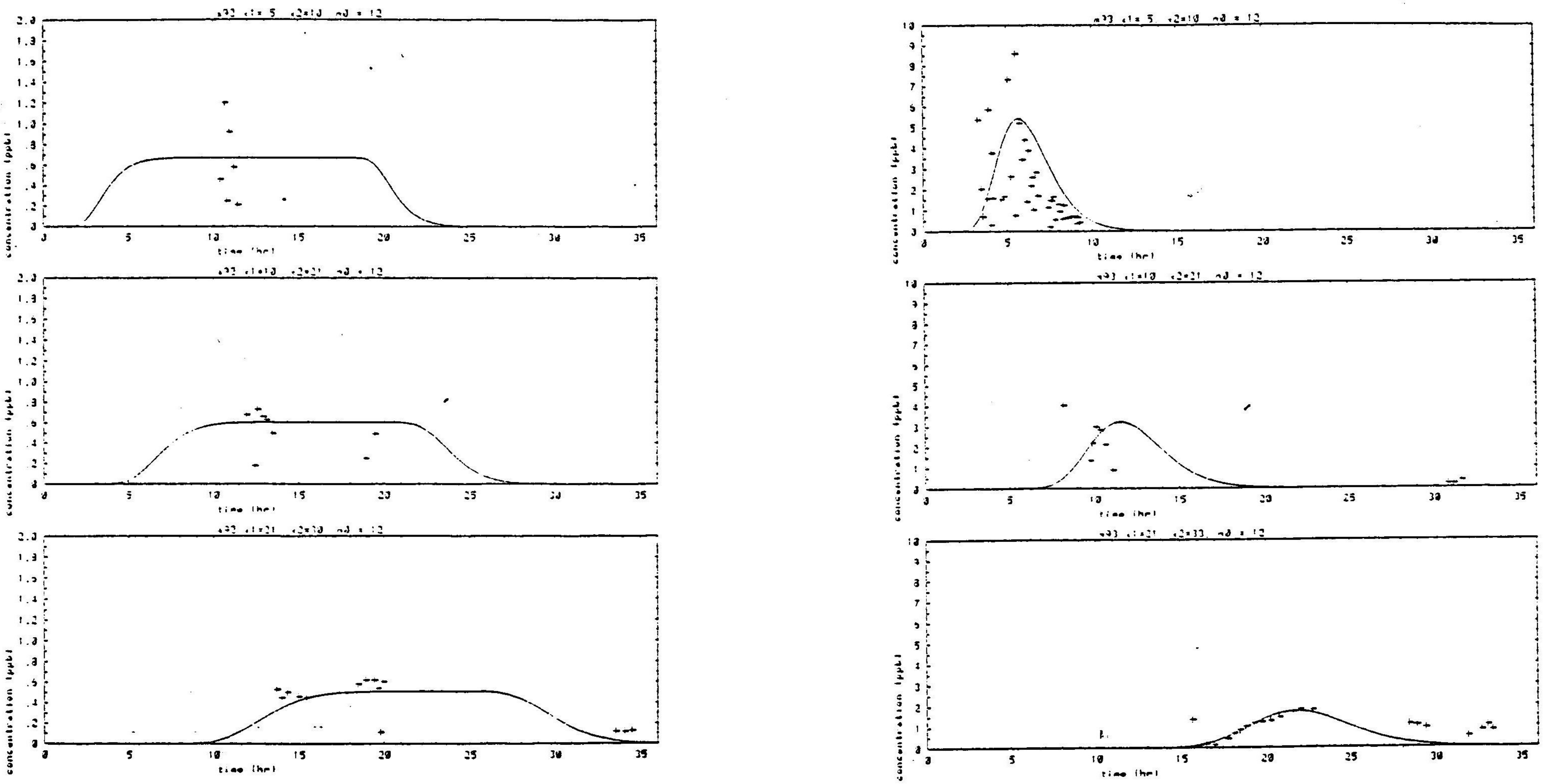

Figure 2. Lower layer average Rhodamine-B ($\bar{c}_3$) at different locations along the Bosphorus, after (a) the continuous dye release, September 1992, and (b) the instantaneous dye release, March 1993. Data points are measurements, and solid line is predicted curve obtained at 7.5 km, 15 km and 28 km distances from the source (vicinity of stations B-5, B-8 and B-15 respectively).

Normal discharge conditions prevailed in the first two dye release experiments, with discharges of $Q_1 = 10000-17000\ m^3/s$, $Q_2 = 5000-7500\ m^3/s$ in August 1992, and $Q_1 = 3000-5000\ m^3/s$, $Q_2 = 11000-15000\ m^3/s$ in September 1992. In March 1992, the upper layer flux was increased significantly ($Q_1 = 20000 - 27000\ m^3/s$), leading to the lower layer discharge to be significantly reduced ($Q_2 = 1000 - 3000\ m^3/s$), *i.e.*close to lower layer blocking. In December 1993, the upper layer was blocked ($Q_1 = 0$), and Black Sea water ($S < 18$) was trapped north of the constriction area. Elsewhere, Marmara surface water ($S \simeq 24 - 26$) and the underlying Mediterranean water flowed towards the Black Sea (total $Q_2 = 20000\ m^3/s$), and submerged under the low salinity wedge of Black Sea water.

In all of these cases, the upper layer mean concentration of dye in the Bosphorus did not increase above 0.4 *ppb* and on the average, comparable to background levels. The interfacial concentrations increased in both of the blocked cases, reaching a maximum of 1.6 *ppb* in December 1993.

The measurements were grouped together within the ranges of 5-10 *km*, 10-21 *km*, and 21-33 *km* from the source, and compared with the analytical solutions of the one-dimensional diffusion equation at distances of 7.5, 15 and 28 *km* (corresponding to the B5, B8 and B15 sections). Examples for the September 1992 continuous release (Figure 2a) and the March 1993 instantaneous release (Figure 2b) cases indicate considerable success of the longitudinal dispersion model. The computations were made with initial masses and adsorption specified above, and suitable velocity and geometrical parameters chosen for the individual cases, resulting in dispersion coefficient estimates of $E_x = 90 - 205 m^2/s$.

The dye distribution in the southern Bosphorus was typically inhomogeneous, as a result of inefficient vertical and horizontal mixing, and the irregular topography immediately south of station B5 (*e.g.*Özsoy *et al.*, 1986). Homogeneity was achieved only in the northernmost end of the Bosphorus.

Dispersion in the instantaneous release case resulted in three orders of magnitude decrease relative to the injection concentration c_d, within 7.5 *km* from the source (B5) about 4-6 hours after injection. In the continuous release case (Figure 2a) the dye concentration decreased only slightly along the Bosphorus because it is only diluted by decay or entrainment losses.

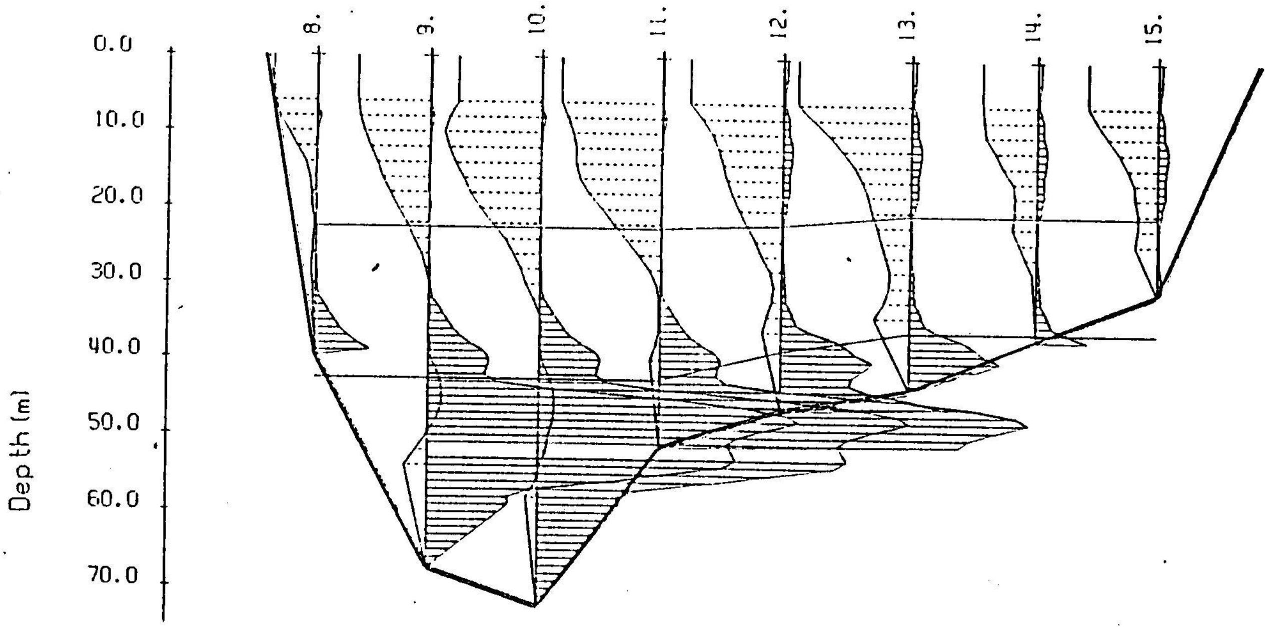

Figure 3. Flux calculations at Section B5, 5 March 1993, 14:22. The dye concentration and normal velocity profiles are depicted in solid and dotted lines respectively at every sample depth.

The simultaneous measurements of current velocity and Rhodamine-B dye allow the calculation of dye fluxes at sections across the Bosphorus, based on fluorescence and velocity measurements. In post-processing, the ADCP and CTD data are matched, extended to data void regions, and the product integrated across the cross-section. An example of the flux calculations, with matched and extended dye and normal velocity profiles, is shown in Figure 3. High values of lower layer dye fluxes are found throughout the monitoring periods, with much smaller values of surface and interfacial fluxes. The flux is then integrated with respect to time to yield total dye mass $M_i = \int\int uc \, dAdt$ passing through the lower layer. 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. These are good order of magnitude verifications of the total transport, compared to the 81 kg and 140 kg estimated respectively for the two cases, accounting for adsorption and decay losses. Given the uncertainties in the methodology, these values, respectively accounting for $\sim$ 67 % and $\sim$ 23 % of the total dye released, are reasonably successful verifications. The reason for a larger disagreement in the second case could be related to flux estimations with missing near-bottom data during nearly blocked flow conditions.

CONCLUSIONS

Both the dispersion computations, and the measurements indicate that the dye is rapidly diluted in the lower layer of the Bosphorus within short distances 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, dilution is of order Q/Q_t, entirely due to the redistribution of wastewater across the channel. We expect the dilution ratio in the continuous discharge to be on the order of 10^{-3} to 10^{-4} for the lower layer waters. In this case, very little change occurs in terms of average concentration with distance along the Strait, resulting from decay and entrainment alone.

One of the most important results of the study is that it verifies the assumptions used in the design. It is shown that the wastewater dilution is similar to salinity (which was used as a conservative tracer in the design stage), despite complicating factors of wastewater buoyancy and three-dimensional effects in the case of the wastewater plume. Some of the dye injected in the lower layer is trapped within the interfacial layer, while a still smaller fraction finds its way to the surface. The amount that reaches the upper layer cannot be established precisely because it is a small concentration on the same order as the background levels. Extreme cases did not lead to critically different results as compared to normal conditions. Comparison with simple models of dispersion in all cases showed good agreement with the lower layer transports in the Bosphorus. 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.

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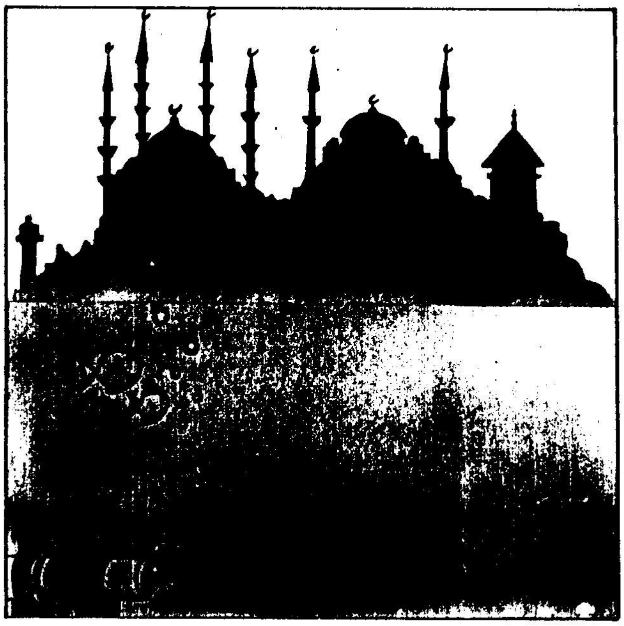

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