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ENVIRONMENTAL MODEL STUDIES FOR THE ISTANBUL MASTER PLAN. PART I: HYDRODYNAMICAL DESIGN BASIS AND MARINE DISPOSAL OF WASTEWATER

I. S. Hansen*,†, H. J. Vested* and M. A. Latif**

** Danish Hydraulic Institute, Agern Allé 5, DK-2970 Hørsholm, Denmark († currently Asian Institute of Technology, Bangkok, Thailand)*
*** Middle East Technical University, Institute of Marine Sciences, Erdemli-Icel, Turkey*

ABSTRACT

A modelling study of the hydrodynamics and spreading of wastewater from existing and future outfalls in the Bosphorus region has been conducted applying a 3-Dimensional model. The modelling is based on SYSTEM 3, which is a general modelling system for baroclinic flow simulating unsteady currents, water-levels, salinity and temperature within the model area. The model set-up covers the Black Sea-Bosphorus-Marmara Sea junction area. The set-up is calibrated by data from a dedicated field program and previous field experience. The model is designed to describe the characteristic features of the flow in the junction area such as the effects of variations in waterlevel differences between the Sea of Marmara and the Black Sea on the important two-layer structure in the strait and the flow fields generated by the upper layer jet in the Bosphorus-Marmara junction. This model has been applied for evaluation of disposal of wastewater and for the subsequent water quality studies. The general use of a baroclinic 3-D hydrodynamic model to simulate disposal of wastewater is discussed. Examples of the application of the model of the junction area to evaluate the different strategies for disposal of wastewater are presented.

KEYWORDS

Bosphorus Strait, Istanbul, Sea of Marmara, Stratified flow, Wastewater discharge, Water quality, 3-dimensional modelling

INTRODUCTION

The metropolis of Istanbul is in the process of reviewing the wastewater strategy and establishing a master plan for the period up to the year 2030. Within this time span the sewerage system is expected to be extended to service from the present 8 millions inhabitants of Istanbul, including the suburbs, to a total of about 20 million people. As part of the master plan a comprehensive environmental impact study, based on advanced 3-Dimensional models, has been carried out in order to determine the marine effects of the different wastewater strategies. The basic components of the wastewater strategies tested are: outfall area, off-shore distance, effluent trapping level and treatment level of the wastewater before discharge.

The description of the study is divided into two parts. Part one presents the set-up of the hydrodynamical model for the Black Sea - Bosphorus Strait - Sea of Marmara (BBM) junction area, the selected design period to be applied in the simulations, results of simulations of the hydrodynamical conditions and the spreading and decay of bacteria in the wastewater plumes. Part two describes the results of the modelling of water quality in the junction area and the modelling of eutrophication in the Sea of Marmara.

OCEANOGRAPHIC CONDITIONS AND DISPOSAL OF WASTEWATER

The study area is oceanographically very complicated. A distinct two-layer system in the Bosphorus Strait is present, where the dense Sea of Marmara water (about 37 ppt) flows towards the north in the lower layer and the less dense Black Sea water (about 18 ppt) flows towards the south in the upper layer. The Sea of Marmara is permanently and strongly stratified, with a top layer 10 - 30 m thick. The Black Sea is also stratified with a top layer more than 100 m thick. The lower layer is fed consistently from the Aegean Sea via the Dardanelles and water in the lower layer flows steadily towards the Bosphorus to pour northward into the Bosphorus lower layer and passes a sill at about a depth of 33 m, which acts as a hydraulic control.

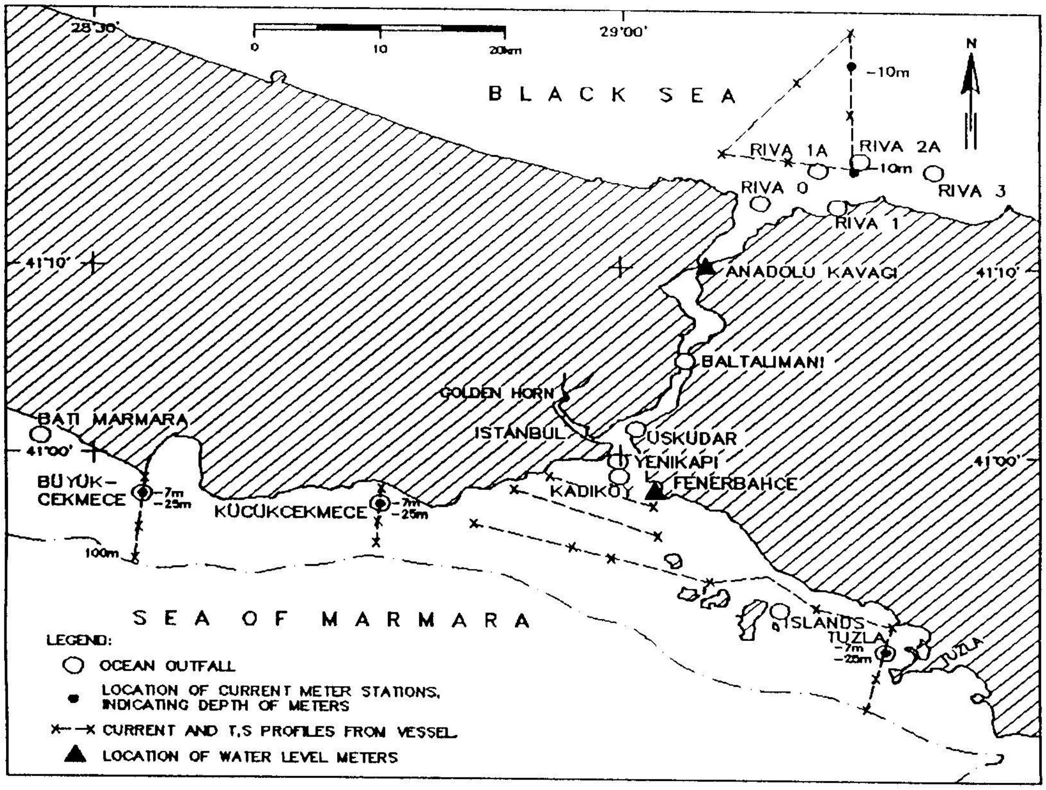


Fig. 1. Study area, location of examined sewage outfalls and positions and transects in field campaign.

The waterlevel difference between the Black Sea and the Sea of Marmara is on average about 0.33 m. The seasonal variability is related to the changes in the adjacent basins, the seasonal heating and cooling cycle, whereas the variations on the time scale for some days are related to the changes in the atmospheric pressure and wind. These variations may dominate the flow and give rise to substantial modifications of the regional flow structure. When the waterlevel difference of the Bosphorus Strait exceeds about 0.45 m the lower layer flow will be blocked by the barotropic pressure gradient, whereas the upper layer flow will increase considerably. The lower layer is on average blocked 10% of the year. Other effects of the changing waterlevel differences are the generation of a strong surface jet and large scale eddies in the Bosphorus-

Marmara junction area, and changing vertical mixing. See also Ünlüata et al. (1990) for an excellent review of the physical oceanography of the Turkish Straits.

In the master planning phase, the questions to be answered in relation to marine effects of wastewater discharged into this area include: what is the interference of the wastewater plumes with the water quality standards like the EC-guideline of coliform concentrations? How big a fraction of the wastewater will be transported to sensitive areas? Will there be significant effects on oxygen and eutrophication conditions and what is the effect of reducing the loadings by treatment before discharge? Fig. 1 shows the potential and existing outfall positions included in this study.

To study the effects of the marine disposal of sewage water under complicated oceanographic conditions as described above and to evaluate the different strategies for wastewater disposal it is necessary to apply a 3D hydrodynamical and advection-dispersion model, which can simulate the currents and mixing conditions responsible for transport and spreading of the effluents. The basis for the 3D model is the modelling system, SYSTEM 3, developed by Danish Hydraulic Institute.

MODELLING TOOLS

The mathematical foundation of SYSTEM 3 is the Reynolds-averaged Navier Stokes equations in three dimensions (1), including turbulence descriptions and variable density, together with the mass conservation equation (2).

$$\frac{\partial u_i}{\partial t} + \frac{\partial (u_i u_j)}{\partial x_j} + 2\Omega_{ij} u_j = \frac{1}{\rho}\frac{\partial P}{\partial x_i} + g_i + \frac{\partial}{\partial x_j}\left(\nu^T\left\{\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right\}\right); \qquad \frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_j}(\rho u_j) = 0 \qquad (1)(2)$$

ρ is the local density of the water, u_i the velocity in the x_i -direction, Ω_{ij} the Coriolis tensor, P the fluid pressure, g the gravitational vector and ν^T the turbulent eddy viscosity. The turbulent eddy viscosity is calculated from the velocity gradients of the flow (Smagorinsky's sub-grid scale formulation) with corrections for buoyancy effects.

The transport or advection-dispersion equations for salt and temperatures (3 and 4) are used together with the hydrodynamical equations and the UNESCO equation of state for the density of water.

$$\frac{\partial(\rho S)}{\partial t} + \frac{\partial}{\partial x_j}(\rho S u_j) = \frac{\partial}{\partial x_j}\left(\rho D_s \frac{\partial S}{\partial x_j}\right); \qquad \frac{\partial(\rho T)}{\partial t} + \frac{\partial}{\partial x_j}(\rho T u_j) = \frac{\partial}{\partial x_j}\left(\rho D_T \frac{\partial T}{\partial x_j}\right) \qquad (3)(4)$$

S is salinity and T the temperature. D_s and D_T are the dispersion coefficients for salt and temperature, respectively, and are related to the turbulent eddy viscosity.

The equations are discretized on a rectangular computational grid and can, with appropriate boundary conditions, be solved by means of a finite difference method. The hydrodynamics equations are solved using a so-called Alternating Directional Implicit algorithm and the advection-dispersion equations are solved by an explicit high order accuracy numerical scheme, see also Rasmussen (1993) and Vested et al. (1992). For a selected period with specified boundary conditions, SYSTEM 3 simulates the unsteady currents, water levels, salinity and temperature distributions within the modelling area.

Two models have been set-up, a Sea of Marmara model and a Black Sea-Bosphorus-Marmara Sea junctions model. The Sea of Marmara model set-up provides hydrodynamic boundary conditions for the southern boundary of the Bosphorus Junctions model and serves as the basis for the regional eutrophication studies, see also Part II. The boundary limits and specifications of the two model set-ups are indicated in Fig 2.

The Sea of Marmara is very deep in some areas (up to 1500 m). However, the computational domain of the Marmara model is confined to the upper 200 m. This assumption is necessary due to computational time constraints and is valid since the baroclinic processes are the subjects for the modelling, ie. location and mixing of the halocline. The Bosphorus Junctions model is restricted by the 100 m depth contour in the Sea of Marmara. This maximum depth corresponds also to the maximum depth of about 100 m in the Bosphorus Strait itself. A vertical resolution of 5 m in both models has been chosen in order to resolve the vertical stratification and to obtain a smooth and undisturbed transfer of the halocline from the Marmara model to the Bosphorus Junction model. However, the top layer of the models has a thickness of about 7.5 m, changing with the actual water level variations.

When the oceanographical conditions in the model area are determined, they form the basis for the subsequent simulations of the mixing and spreading of sewage water from the ocean outfalls. These simulations are performed by applying a 3D particle module of SYSTEM 3, where the effluent is simulated by particles. These are advected by the simulated 3D velocity field and the dispersion of the effluent is modelled by a random-walk technique.

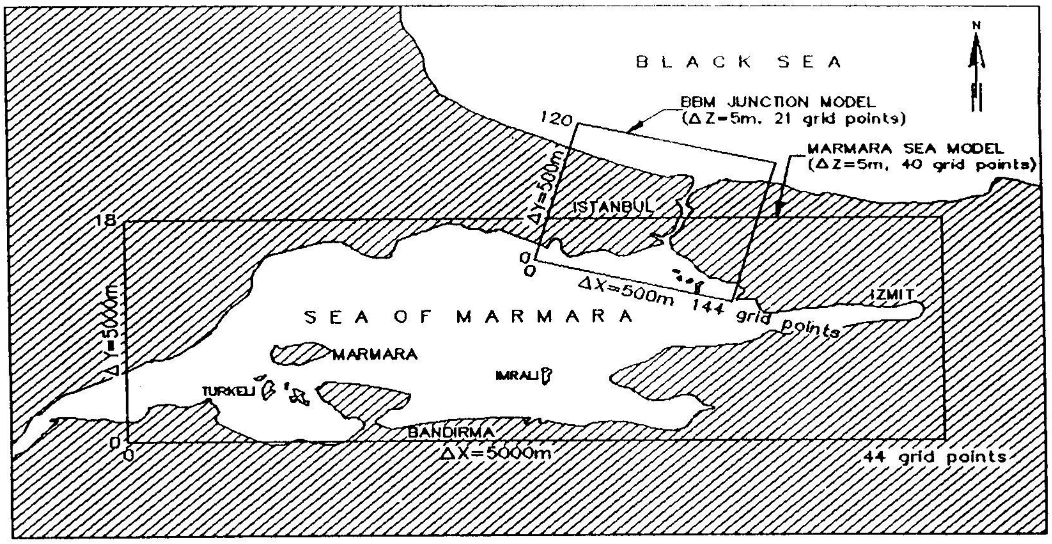


Fig. 2. Overview of model areas and specifications.

The 3D concentration fields can be determined by mapping the particle distribution on the computational grid. The dispersion coefficients have been adjusted to take into account vertical stratification (Richardson Number effect) and unresolved horizontal mixing by calibration with field experiments of release of dye in the Yenikapi ocean outfall (METU 1992).

DESIGN PERIOD AND HYDRODYNAMICAL RESULTS

To prepare reliable model results for the Bosphorus junction it was necessary to complement the extensive oceanographic observations already in existence with observations dedicated to the modelling work. For the present study supplementary current statistics from different key positions and flow structure measurements from the two junction areas were needed. Fig. 1 shows the location of the fixed recorder stations and the survey lines and stations of the intensive profiling undertaken as part of the present study. The fixed measurements started 16-18 September 1993 and ended 29 October 1993. Eight fixed salt, temperature and current meters were deployed, supplemented by two waterlevel recorders measuring relative to geodetic fix points. The intensive profiling survey took place from 22 September to 5 October 1993 including acoustic doppler current profiling (ADCP) in depths along 8 lines and stratification profiling (CTD) at 38 stations. The weather conditions during this period can be characterised as relatively calm with wind conditions representative for a summer situation. The waterlevel differences between the Black Sea and the Sea of Marmara average about 0.32 m and range between 0.05 and 0.75 m in the monitoring period, in good agreement with the long term average value of 0.33 m. The water column was strongly stratified as expected. Generally, the monitoring showed vertical decoupling of the currents at the interface layer during strong upper layer currents, as well as horizontal formation of eddies in the Bosphorus - Marmara junction around the Bosphorus surface jet for large discharges.

The adopted simulation period, referred to as the design period, was selected in order to represent a typical 14 day period representative of the summer conditions in the junction area. An examination of the monitoring period showed that the period 14-27 October 1994 was representative, at an acceptable level, of the general summer conditions with respect to wind conditions and atmospheric pressure, i.e. the currents observed during this monitoring period are believed to be representative for summer conditions. Long-term current measurements are not available to varify this assumption. However, the sea level across the Bosphorus was chosen to vary in time according to the long-term average values, to fit statistical purposes. Concerning the currents in the Black Sea - Bosphorus junction, a variation with the main features of the actual measured currents was applied, see also Fig. 3.

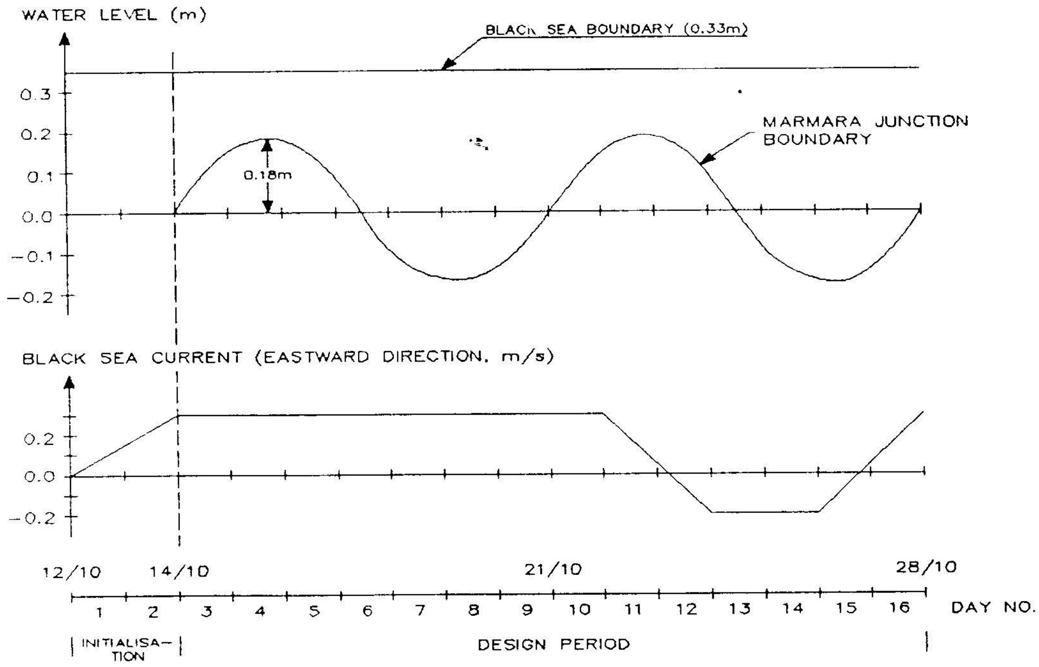


Fig. 3. The variation of sea levels and currents in the Black Sea during the simulation period

The modelled hydrodynamical results during the design period were validated with respect to vertical profiles and discharges in the Strait, horizontal variability and current statistics from the fixed stations during the monitoring period. Compared to the observations in the monitoring period the adopted design period was found to represent the mesoscale conditions in the two junction areas as well as in the Bosphorus Strait (see Fig. 4). It is thus possible to extract information from this period on currents and mixing conditions for periods without blocking of any of the layers in the Bosphorus Strait for periods

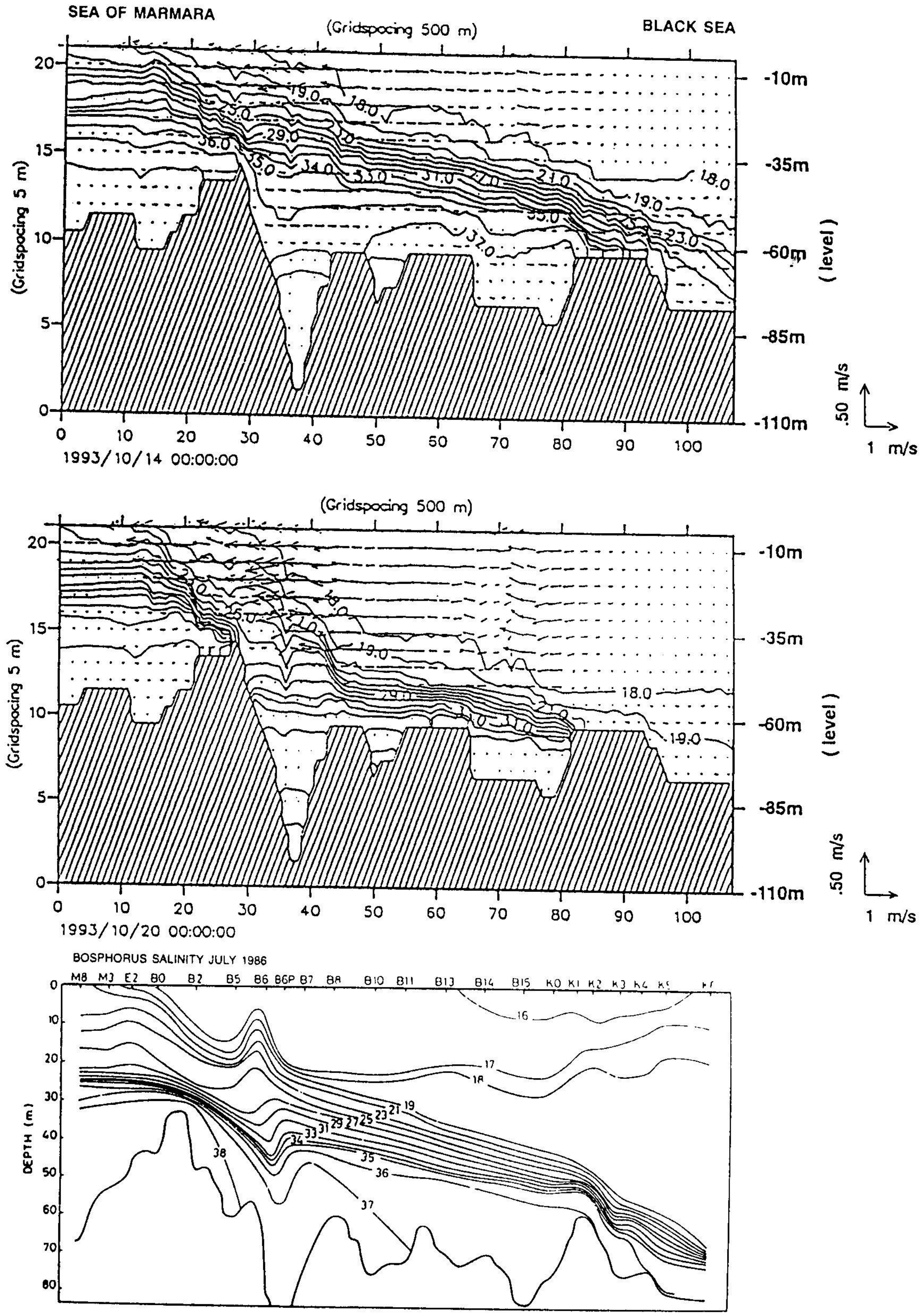


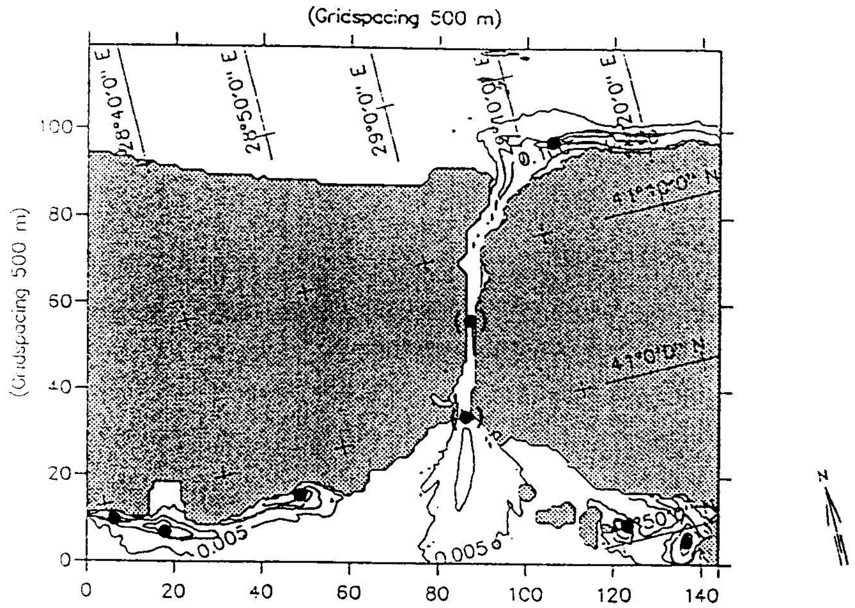
Fig. 4. Calculated salinity (ppt) transects through the Bosphorus Strait at typical flow conditions (top) and during blockage of a lower layer flow (centre) and observations (Ünlüata et al. 1990).

representing occurrence of lower layer blocking in the Bosphorus Strait for average conditions in the Black Sea area and for average conditions in the Bosphorus - Marmara junction.

RESULTS OF MODELLING OF WASTEWATER CONDITIONS

The particle approach for the modelling of the wastewater plumes is applied with the purpose of focusing on the horizontal spreading of the wastewater. The initial wastewater dilution during the rising of the wastewater from the diffusers is not modelled directly. Instead the level, where the horizontal plumes start, is specified. This may be close to the surface (surface trapping) or below the surface in the interface layers between the upper and lower well-mixed layer. For the Bosphorus outfalls the initial level of the horizontal spreading can also be in the lower layer itself, as the current here is assumed to be sufficient for a large initial mixing. The actual trapping level for the different effluents is thus an input parameter in the modelling for master planning purposes. Later it is up to the technical design of the outfalls to obtain the decided trapping levels.

The particle simulations have been applied for two purposes: to check the compliance with standards for coliform concentrations and to assess the fraction of effluent for the individual outfalls, which ends up in either the Black Sea, the Sea of Marmara or, for initial submerged trapping, is mixed into the upper layer. To assess these conditions the Particle module has been developed to include a first order decay for the coliform, where the decay rate is dependent upon, among other things, the temperature and the light intensity in the actual depth of the particle. Furthermore, statistical software has been included to assess the frequency of exceedance of specified levels of concentration and to determine the particle flux through pre-selected cross sections in the model.



Isolines: 0.005, 0.1, 0.2, 0.5

Fig. 5. Design period exceedance frequency of 100 E.Coli/100 ml for year 2030 scenario with biological treatment of effluent and surface trapping of effluents in the Sea of Marmara. The figure shows the frequency in the upper 7.5 m. of the water column. Dots indicate discharge locations with parentheses used when discharge is subsurface .

The applied guidelines of coliform concentrations in the EC-standards for bathing areas along the coast are operating with the level 2000 E.Coli/100 ml not to be exceeded more than 5% of the time and recommending that the level 100 E.Coli/100 ml is not exceeded more than 20% of the time. Fig. 5 shows the results of the exceedance of 100 E.Coli/100 ml for one of the simulated strategies.

DISCUSSION AND CONCLUSIONS

The conducted modelling study of the hydrodynamics and spreading of wastewater from existing and future outfalls in the Bosphorus region is an example of the application of probably the most advanced type of modelling tools available. The applied SYSTEM 3 is a full 3D model for barotropic and baroclinic flows. Application of a model of this type for regional assessments in a relatively open and dynamic area such as the BBM junction area requires a large effort. Firstly the forcing of the model, i.e. boundary condition, should be well known. Specifying these is a general 3D model problem, because waterlevel, vertical salinity and temperature profiles must be known along all boundaries. Often the best way to achieve these data is to transfer boundary data from a coarser model covering a larger area, where the boundary data is more easily specified or where the accuracy of the boundary data has less significance. In the Bosphorus modelling the transfer technique from a model covering the entire Sea of Marmara was applied. Besides measurements for boundary data, data should also be available for validation of the model performance. These data also need to include the vertical variation, thereby increasing the necessary monitoring efforts.

The development of efficient numerical algorithms and high speed computers has now made it possible to perform 3D simulations of regional seas, in spatial and time resolutions where the detailed mixing and flow structures can be simulated. The combination of simulated 3D flow fields and the particle trace technique for determining the spreading is a powerful tool for assessing the 3D concentration fields resulting from many different sources. When the advanced modelling of currents and concentration fields is combined with software for integrating currents, concentrations, discharges and fluxes of substances as well as statistical processing it becomes a very valuable contribution to the difficult task of decision-making for the future implementation of a wastewater strategy. In the Istanbul modelling study a total of 8 main alternatives have been analyzed with respect to coliform distribution using the present model set-up.

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