CHAPTER 182

2 - D CIRCULATION IN THE SARONIC GULF

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ABSTRACT

The paper refers to mathematical modeling of the 2-D hydrodynamic circulation in the Saronic Gulf, in Greece. The finite element method is followed to evaluate the flow behaviour. Two grids are employed, a coarse one for initial model adaptation and a finer one for a more detailed study of circulation patterns. Actual tide data are obtained at the boundary of the domain and a typical compound tide is introduced; however residual tidal currents are found to be negligible. Wind-generated flow fields under several prevailing wind directions are determined and their comparison to qualitative field evidence is satisfactory. Furthermore, a possible surface tilt along the open boundary associated with large scale circulation in the Aegean Sea, is studied and shown to produce significant motion in the Gulf. Based on circulation patterns obtained, preliminary estimates of dispersion from a proposed sea outfall for Athens sewage can be made. Further work proceeds towards quantitative verification of the model in connection with the proper description of forcing mechanisms and their superposition.

INTRODUCTION

The Saronic Gulf is a coastal water body located in the vicinity of Athens, the capital of Greece, as shown in Fig. 1. Due to its location

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and the natural beauty of its coastlines and islands it has a high recreational value for over 4 million inhabitants of Athens and nearby towns as well as for many thousands of visitors. Besides, it has economic importance associated with a variety of human activities in the area. However, the marine environment has been threatened in recent years due to increasing pollution loads discharged into the water body, coming from domestic sewage, industrial effluents and also ship traffic to and from the port of Piraeus. Environmental concerns have risen in connection with the planning of a new treatment plant and sea outfall for the sewage of Athens metropolitan area, which could provide the opportunity for significantly reducing one of the major sources of pollution of the gulf. In this context it is desirable to examine the large scale characteristics of flow in the gulf, so that the far field impact of substances introduced into it may be assessed.

Up to now the hydrodynamic behaviour of the gulf is not well understood [1]. Despite considerable field measurement efforts undertaken since the mid-seventies the data base is yet insufficient for evaluating the overall circulation. This is so because the gulf seems to be an extremely complex water body, both in terms of geometrical configuration and in terms of flow-generating mechanisms. In fact, in the absence of a strong tide, as is typical in the Mediterranean Sea, several forcing mechanisms are potentially important, resulting in generally weak but highly variable currents.

The complexity of the problem suggests a mathematical modeling approach. As a first approximation a two-dimensional description of the circulation is sought in this paper, through adaptation of pertinent finite element models. The determination of the circulation patterns under a variety of conditions allows an assessment of the major forcing mechanisms. Furthermore, preliminary estimates of the extent of contamination from the proposed new outfall can be made.

PHYSICAL CHARACTERISTICS OF THE GULF

As shown in Figure 1, the Saronic gulf has an area of approximately 2600 Km^2 and is connected to the Aegean Sea through a 42 Km opening at the SE. Its bathymetry and geometry are highly complex, with irregular boundaries and many islands. The two main islands of Salamina and Aegina essentially divide the gulf into three major parts. The outer gulf, at the SE, is connected to the open sea and has depths gradually decreasing from about 200 m at the boundary to 100 m towards the inner gulf. The latter, at the NE, has depths generally less than 100 m and is of major interest from the environmental point of view. Finally the western gulf has a pronounced depth variability, with depths locally exceeding 400 m; its water masses are only indirectly connected to the open sea, being exchanged through the passages north and south of Aegina island with the inner and outer gulf, respectively.

Temperature and salinity measurements taken at various stations in the gulf have indicated that the density distribution over the water column is essentially uniform during the winter season, while considerable stratification develops during the summer. Therefore the assumption of vertically well-mixed conditions, inherent in the implementation of 2-D model-

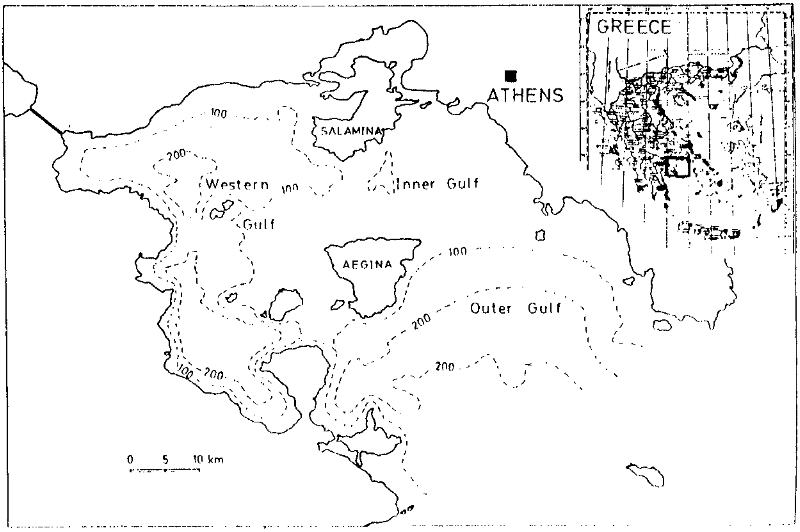

Figure 1. Map of the Saronic Gulf.

ing, is justified by available observations for the winter months, i.e. December to March.

NUMERICAL MODELING

The geometrical complexity of the Saronic Gulf suggests the application of the finite element method. At this stage, a simple and reliable finite element model with linear traingles, code-named CAFE [3], was implemented. The model solves the following depth-integrated equations of continuity and momentum, under the assumptions of constant density and hydrostatic pressure distribution, as described in detail by Wang and Connor [4]:

$$\frac{\partial n}{\partial t} + \frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} = 0 \qquad (1)$$

$$\frac{\partial q_x}{\partial t} + \frac{\partial}{\partial x}(\bar{u}q_x) + \frac{\partial}{\partial y}(\bar{v}q_x) - fq_y = -\frac{\partial F_p}{\partial x} + \frac{\partial F_{xx}}{\partial x} + \frac{\partial F_{xy}}{\partial y} + \frac{1}{\rho}(\tau_x{}^s - \tau_x{}^b) +$$

$$+ \frac{1}{\rho}\left(p^s \frac{\partial H}{\partial x} - gn\frac{\partial h}{\partial x}\right) \qquad (2)$$

$$\frac{\partial q_y}{\partial t} + \frac{\partial}{\partial x}(\bar{u}q_y) + \frac{\partial}{\partial y}(\bar{v}q_y) + fq_x = -\frac{\partial F_p}{\partial y} + \frac{\partial F_{xy}}{\partial x} + \frac{\partial F_{yy}}{\partial y} + \frac{1}{\rho}(\tau_y{}^s - \tau_y{}^b) +$$

$$+ \frac{1}{\rho} \left(p^s \frac{\partial H}{\partial y} - gn \frac{\partial h}{\partial y}\right) \qquad (3)$$

where:
$-h, n$ = bottom and free surface elevation with respect to mean sea level
H = $h + n$ = total depth
$q_x = \int_{-h}^{n} u dz = \bar{u}H$ = specific flux along x
$q_y = \int_{-h}^{n} v dz = \bar{v}H$ = specific flux along y
$\bar{u}, \bar{v}$ = depth-average velocities along x,y
f = $2\omega \sin\varphi$ = Coriolis parameter
p^s = atmospheric pressure, acting on the free surface
τ_x^b, τ_y^b = bottom shear stresses
τ_x^s, τ_y^s = surface shear stresses, due to wind
$F_p = \frac{1}{\rho} \int_{-h}^{n} p dz - \frac{1}{2} gh^2$ = hydrostatic force relative to $n=0$
$F_{xx} = \int_{-h}^{n} (\nu \frac{\partial \bar{u}}{\partial x} - \overline{u'^2} - u''^2) dz$ = integrated internal stress due to molecular viscosity, turbulent velocity fluctuations and spatial deviations of velocity from depth-average value.
F_{yy}, F_{xy} = respective integrals of internal stresses along yy, xy.

The above equations, with proper parametric expressions for the bottom, surface and internal stresses, are transformed through the Galerkin method to a system of ordinary differential equations in time for the unknowns n, q_x, q_y, which is solved by a split-time integration technique [3,4].

The problem was approached at two levels of detail. Initially a coarse grid was used for model adaptation and calibration in the study area and to obtain an understanding of the importance of the forcing mechanisms at minimum computational effort. The coarse grid is shown in Figure 2. It consists of 112 nodes and 160 triangular elements, with a grid size of the order of 2 to 5 Km. Only two major islands are represented, while the narrow passes between Salamina island and the mainland are considered as closed. Subsequently, a finer grid was applied, in order to study in sufficient detail the circulation generated by the dominant forcing mechanisms and further proceed to preliminary estimates of dispersion from the new sea outfall. This finer grid is shown in Figure 3. It consists of 233 nodes and 373 triangular elements, with a grid size ranging from 0,8 to 3 Km, and it includes three more islands.

In both grids, a zero flux normal to all land boundaries was prescribed, while at the open boundary a specified water level variation was introduced. The computational time step for the coarse grid was 100 sec. and for the fine grid 50 sec. The modeling applications were performed on the CDC Cyber-171 computer of NTUA. The computer time required for the simulation of 1 day real time was about 15 cpu min. for the coarse grid and 60 cpu min. for the finer grid.

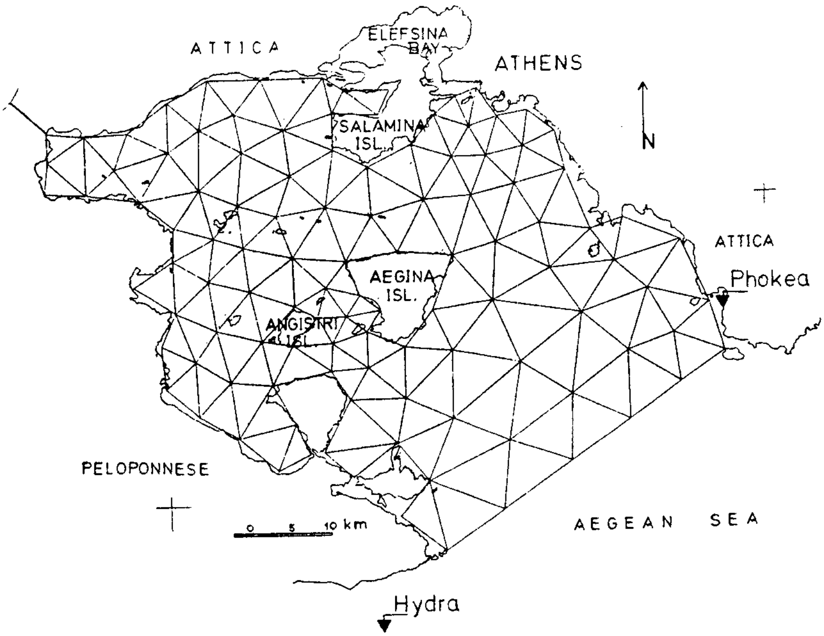

Figure 2. Coarse finite element grid

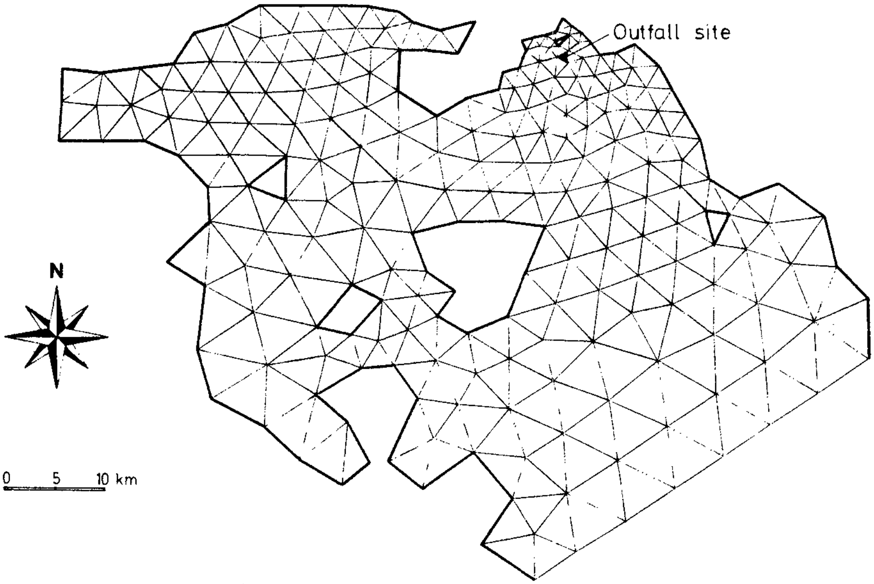

Figure 3. Fine finite element grid

CIRCULATION STUDIES

Coarse grid

Three main forcing mechanisms were examined at a preliminary level with the coarse grid: Tide, wind and a surface filt along the open boundary. In particular, with respect to tide, earlier estimates based on tidal data from Piraeus harbour, at the northern coast of the gulf, have indicated a mean tidal amplitude of about 10cm. Employing such a uniform sinusoidal tidal forcing was found to produce weak and reversing tidal currents resulting in practically no net motion over the entire gulf. In order to determine possible amplitude and phase differences along the open boundary an effort to obtain actual tide data was undertaken. Two self-recording tide gauges were installed near the two ends of the boundary, at Phokea and Hydra, as shown in Fig. 2. Measurements were taken for a period of about three months, from September to December 1984. The half-hourly readings were subsequently analysed by means of Fast Fourrier Transform and harmonic analysis. Four main components were clearly identified, corresponding to two diurnal and two semidiurnal tides, which were found to contain almost all the energy of the signals. These components were then synthesized to produce a "typical" tidal water level variation at the two points, as shown in Figure 4. This typical compound tide of duration 4T= 180,000 sec. was then assumed to repeat itself for numerical modeling purposes. To obtain elevations at intermediate boundary nodes linear interpolation was used at each time step.

As evident from Fig.4, there is a variable elevation difference along the open boundary, therefore some residual currents are to be expected in this case. Figure 5 shows depth-averaged water particle motion obtained for the "typical" tidal forcing acting for 2 weeks. It is seen that appreciable net movement occurs only close to the boundary. Consequently, it may be concluded that tidal flushing cannot be relied upon to reniew the water masses of the Gulf, and especially those of the inner gulf where most of the pollution loads are introduced.

After the above findings, it is clear that the wind-driven circulation should be of primary importance. Still, the resulting depth-averaged currents cannot be very strong due to the relatively large depths of the study area. According to long-term wind records the prevailing winds in the area are from northerly directions. In particular for the winter, excluding periods of no wind, the most frequent wind directions are: N 26.5%, NE 19.0% and S 12.3%. Since reliable wind measurements were available from one station only, a study of uniform wind from several directions over the entire gulf was conducted. In all cases a zero surface elevation at the open boundary was specified. It was found that steady state flow was reached about 1.5 day after the initiation of forcing.

As a third circulation mechanism, a possible small surface tilt along the open boundary was tried. The response of the gulf was found to be quite sensitive to such a forcing. The physical justification for introducing a surface tilt lies in observational evidence of a "permanent" inflow along the eastern coastline of the gulf associated with the large-scale circulation in the Aegean Sea. No quantitative information on this

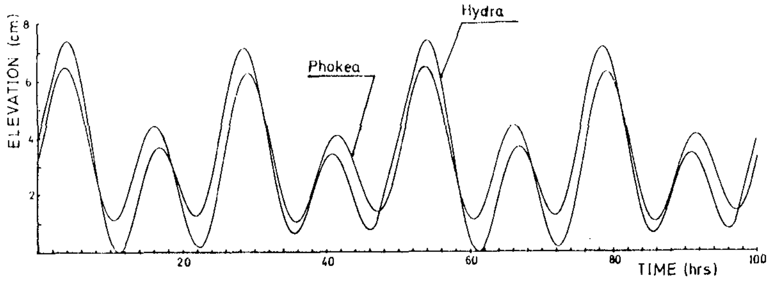

Figure 4. Typical compound tide at open boundary.

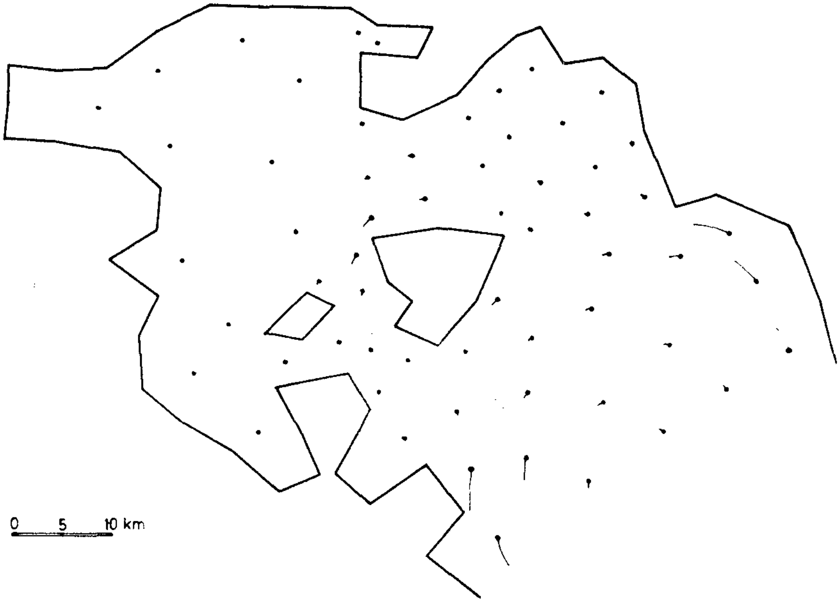

Figure 5. Mean water particle paths under typical tidal forcing for 14 days.

inflow is presently available, and it presumably has significant long-term variability. Yet, its qualitative effect on the circulation of the Saronic Gulf can be possibly simulated by the specification of a higher surface elevation at the eastern end of the open boundary.

Fine Grid

The fine grid was implemented for obtaining more detailed circulation patterns and as a necessary level of discretization for introducing the source of effluent dispersion. With this grid primarily the wind-generated circulation was examined. Figures 6,7 and 8 present the steady-state mean velocity field for the three most frequent wind directions in the study area, that is N, NE and S, respectively. The upper part of each figure, denoted by (a), presents the model results for a constant 20 knot wind, while the lower part, denoted by (b), shows the respective circulation patterns near the surface estimated by Dugdale and Hopkins [2] based on a qualitative synthesis of available oceanographic data and observational evidence at the time.

For the most common north wind the model (Fig. 6a) indicates an inflow from the middle part of the opening and outflow near the two ends. A clockwise gyre develops in the eastern part of the inner gulf and an incomplete counterclockwise motion to its left, leading to outflow towards the western gulf. The upper part of the latter is covered by an extensive clockwise gyre, while a small counterclockwise gyre is seen near the westernmost corner. Two other notable features are the outward coastal current from Athens to the SE and the counterclockwise motion around the island of Aegina. As seen in Fig. 6b the above findings agree reasonably well with the estimates of Dugdale and Hopkins. The major discrepancy lies in the appearance of an opposite current along the northern coast of Aegina, associated with the development of a second, clockwise gyre in the inner gulf.

Results of the model for NE wind (Fig. 7), and S wind (Fig.8) also show generally satisfactory overall qualitative agreement with the respective patterns of Dugdale and Hopkins. Discrepancies are observed primarily in the area between Salamina and Aegina and the adjacent part of the inner gulf. These may well be due to spatial variability of the wind associated with the mountains and other topographical features surrounding the gulf; they could also be caused by local bathymetric detail or even by small horizontal density differences which are not accounted for in the model.

Figure 9 presents the steady-state velocity field for a 1cm elevation difference between the ends of the open boundary. The resulting motion is more pronounced in the outer gulf with inflow at the eastern part and outflow at the western part. An opposite, clockwise, gyre is seen to develop in the inner gulf; flow towards the west is observed in the passage between Salamina and Aegina, while motion continues around Aegina in a counterclockwise sense. It is seen that the effect of such a small surface tilt can be comparable to that of moderate to strong winds and therefore further study is warranted.

Quantitative verification of the model predictions has not yet been made. To this end, limited current meter data obtained at certain locations of the gulf are being analysed; however, preliminary evidence indicates that the model generally underpredicts the velocity magnitude. It is anticipated that satisfactory verification will require further numerical experimentation with improved quantification and superposition of forcing

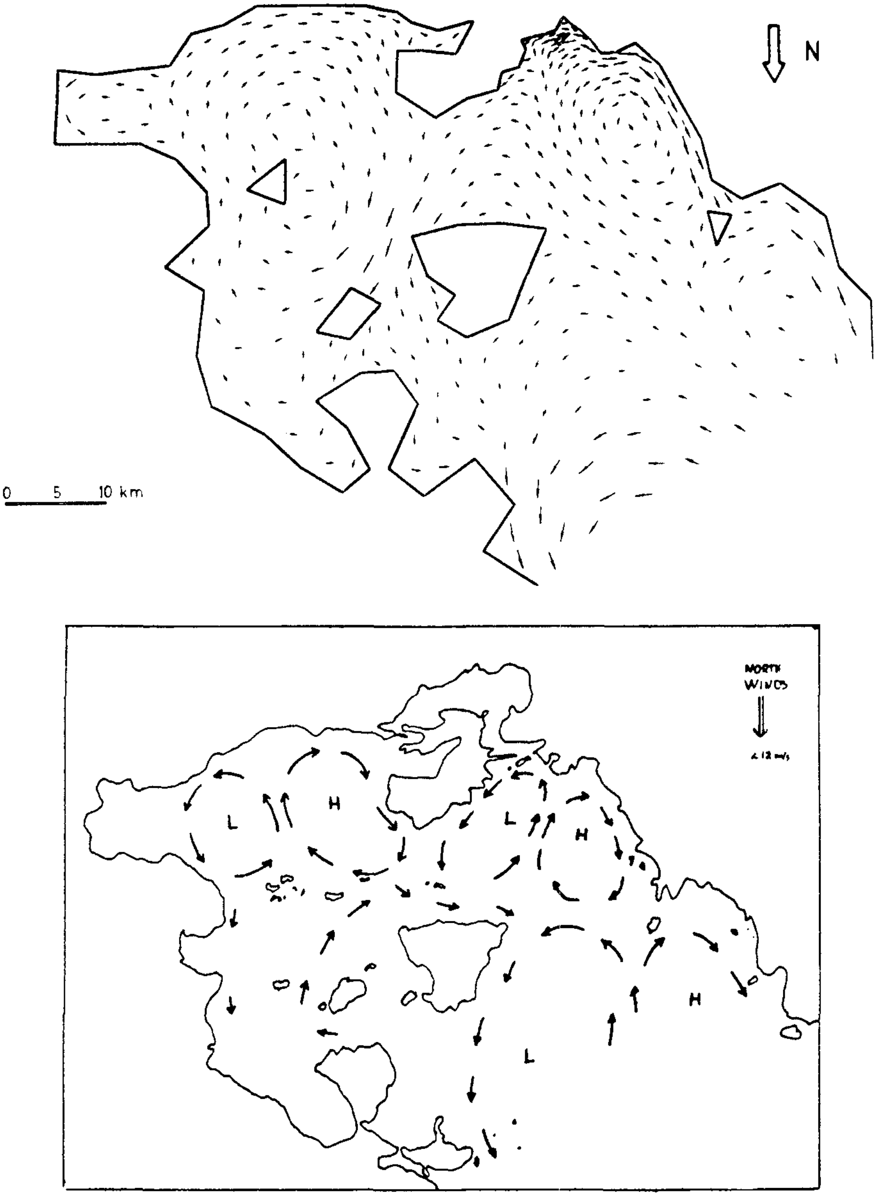

Figure 6. Steady-state circulation for North wind: (a) Model results, (b) Patterns estimated by Dugdale & Hopkins.

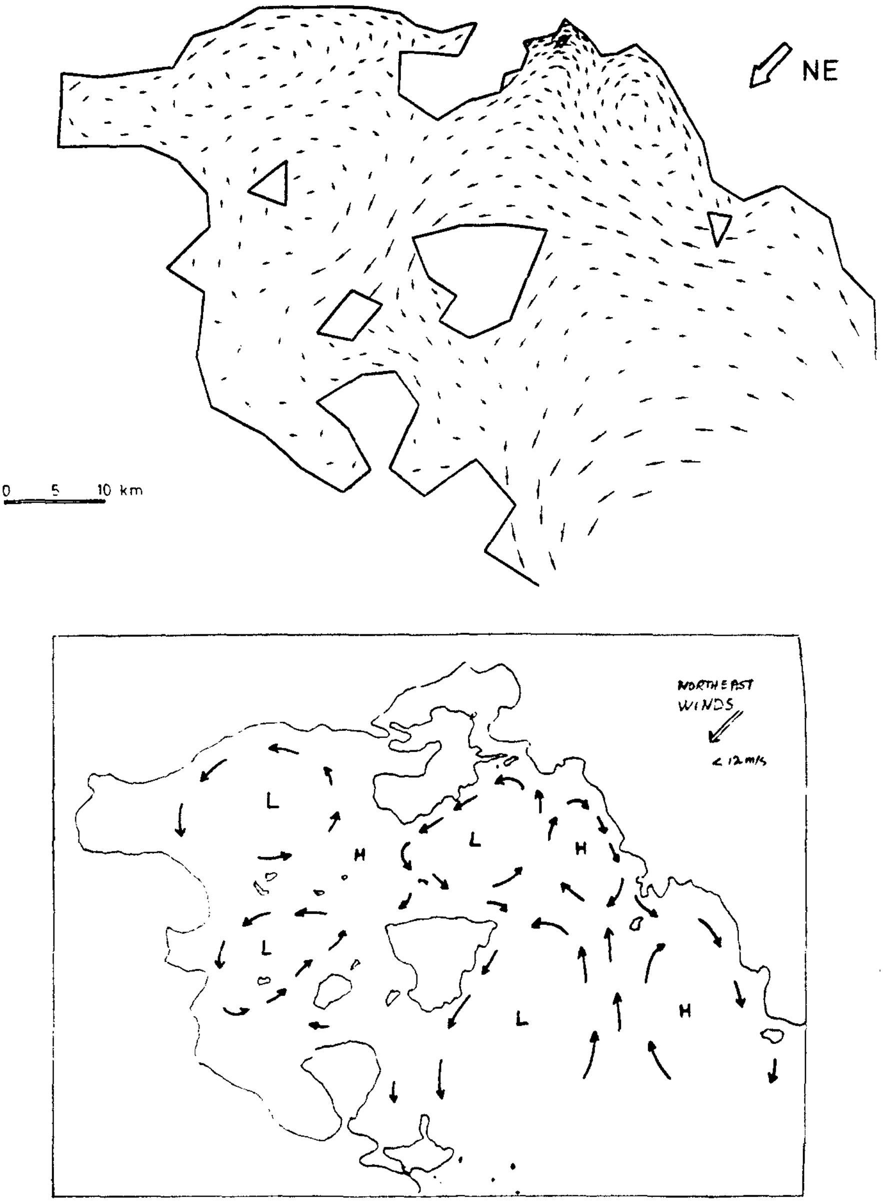

Figure 7. Steady-state circulation for Northeast wind: (a) Model results, (b) Patterns estimated by Dugdale & Hopkins.

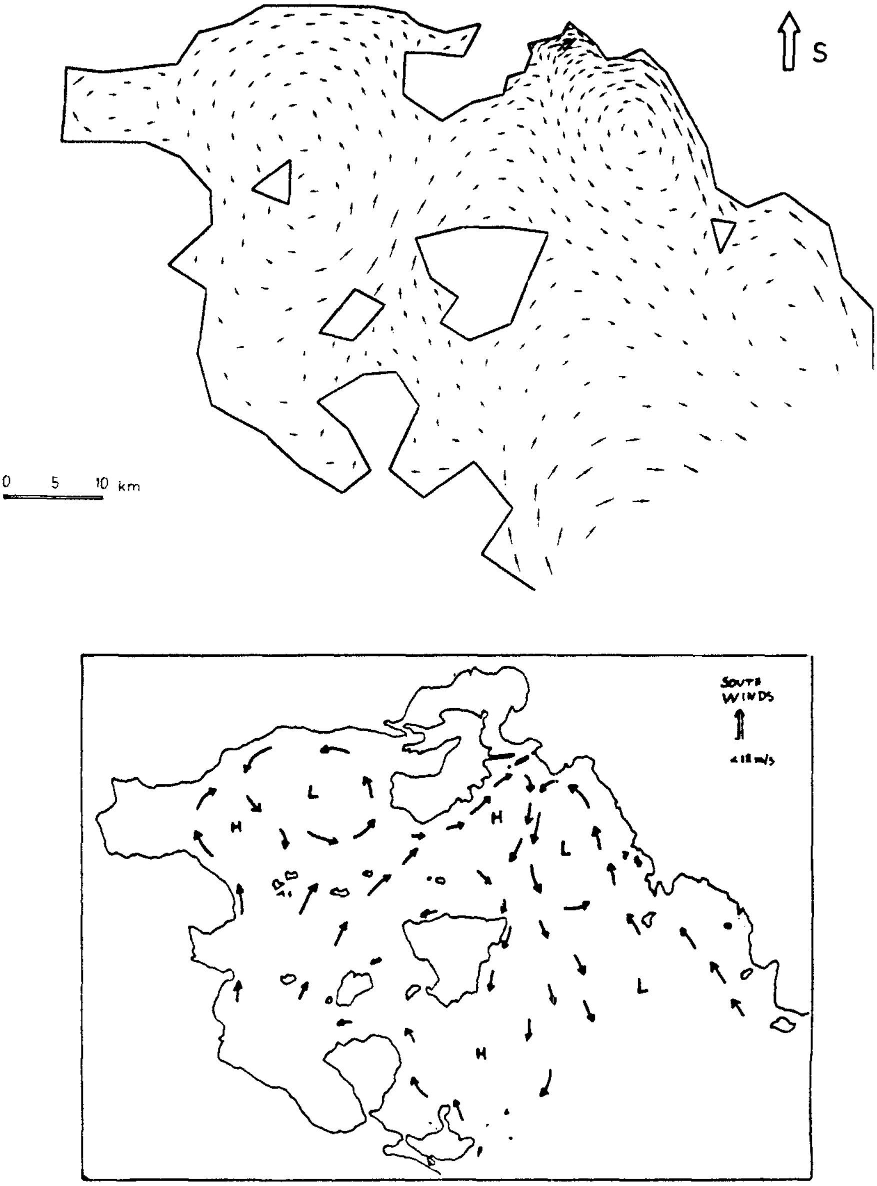

Figure 8. Steady-state circulation for South wind: (a) Model results, (b) Patterns estimated by Dugdale & Hopkins.

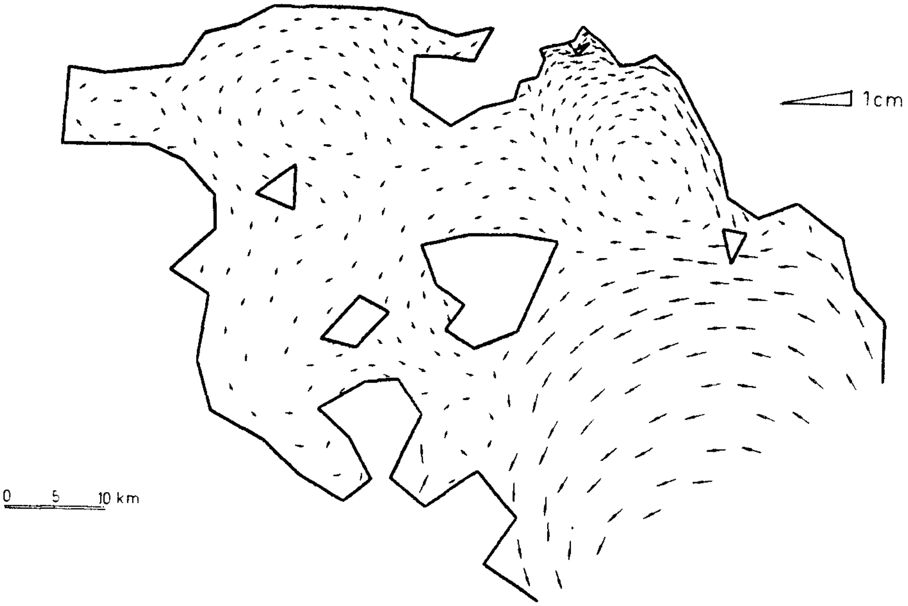

Figure 9. Steady-state circulation for a 1 cm surface tilt of the open boundary.

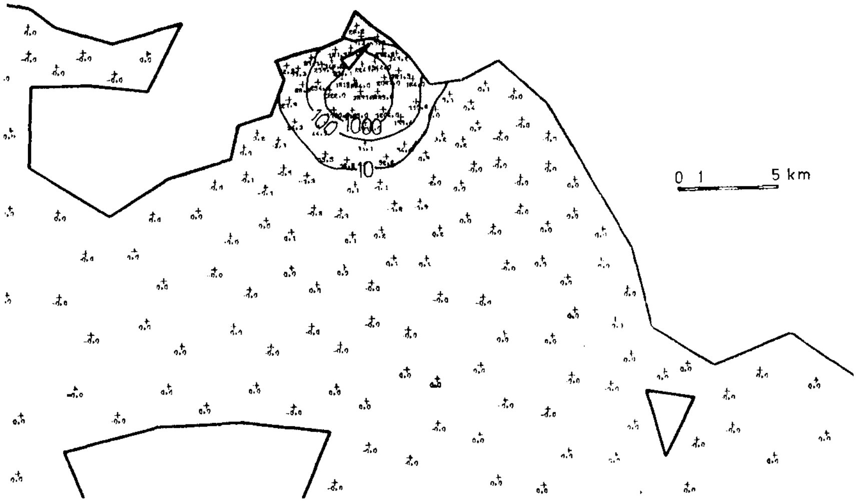

Figure 10. Computed depth-average coliform concentrations (in counts/100 ml) for new outfall.

mechanisms as well as adjustment of some model parameters and boundary conditions.

DISPERSION STUDIES

The dispersion of effluent from the proposed sea outfall was studied with the fine grid shown in Figure 3, where the source is represented by the shaded triangle. The projected annual average discharge of sewage is about $10 m^3/sec$. Assuming only preliminary treatment prior to sea disposal, the concentration of coliform in the effluent would be of the order of 10^7 counts/100 ml. Assuming further a decay rate of $k=0.8x10^{-4} sec^{-1}$, corresponding to an average day-night time $T_{90}=$ 8 hrs, and an estimated constant dispersion coefficient of the order of $E = 40 m^2/sec$, the dispersion of coliform may be examined for any desired circulation pattern already obtained.

Figure 10 presents steady-state depth-averaged coliform concentration results (in counts/100 ml) under conditions of N wind. It is seen that appreciable concentrations, over 100 counts/100 ml, are confined to a small area around the source, so that no significant contamination of beaches in Attica (to the SE) or Salamina (to the SW) should be expected under the conditions examined. It is further noted that results of other wind cases show little sensitivity of steady-state isoconcentration patterns with wind direction . The above findings strongly depend on the high decay rate used. Evidently, for showly decaying pollutants, e.g. nutrients, the dispersion patterns would be much more extensive and more influenced by meteorological conditions.

CONCLUSIONS

In this paper, the implementation of finite element models for studying the hydrodynamic behaviour of the Saronic Gulf was presented. It was found that wind and a possible surface tilt along the open boundary are of major importance in determining the 2-D circulation in the gulf Actual tide data at the opening were collected and analyzed; yet, the contribution of the tide in the net circulation was found to be negligible. Limited verification with available field evidence was satisfactory in terms of qualitative agreement with model results. But more work is needed on quantitative verification against current meter data, as well as on further examination and quantification of forcing mechanisms, such as the spatial variability of the wind over the study area, the long-term inflow from the Aegean Sea, or any small horizontal density differences that could appreciably change the results of the 2-D circulation. Eventually, the examination of vertical variability will be required for studying the hydrodynamic behaviour under stratified conditions.

The accuracy of circulation patterns will be critical for assessing the dispersion of slowly decaying substances from the proposed sea outfall. However, for fast decaying pollutants, such as coliforms, the extent of appreciable contamination, based on the results presented, is expected to be restricted within the inner gulf.

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