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Modeling Stratification – Mixing Processes at the mouth of a Dam–Controlled River

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Abstract: In this paper the question of freshwater induced stratification at the mouth of a dam-controlled river is addressed. Understanding the development and breakdown of stratification is a key environmental issue for river mouths, since it largely determines the vertical fluxes of water properties such as heat, salt, momentum and nutrients. An intensive monitoring program (vertical profiles of salinity, temperature and water flow) has been undertaken along Strymon river estuary during the spring and summer period, when river flow is man-controlled from Kerkini dam, according to irrigation needs. The main target of this monitoring program was to provide information on the stratification – mixing conditions prevailing in the area of Strymon River mouth under different water flow regimes. A stratification – mixing model in terms of the water column potential energy (ϕ) was developed and applied in Strymon River, to account separately for the local contributions to stratification (solar heating and freshwater buoyancy) and mixing (wind and bottom shear stresses). The model was run under two different scenarios (the influence of Kerkini dam and the absence of Kerkini dam) to assess the impact of water retention on the stratification conditions at the river mouth. Results show that the ϕ_{TOTAL} – term was strongly dependent on the density gradient induced by river flow, especially during spring and early summer, when the operation of Kerkini lake reduces stratification by approximately 14-59%. The mean annual water column potential energy (ϕ_{TOTAL}) was also reduced by approximately 13%.

Key words: stratification, water column dynamics, potential energy, Strymon River.

1. INTRODUCTION

Stratification conditions of the water column in estuaries reflect the continuous competition between the stratifying influences of vertical gravitational circulation induced by buoyancy inputs and the mixing produced through mechanical stirring by winds and tides. Furthermore, stratification appears to be a key environmental parameter for estuarine ecosystems, since it controls the vertical distribution of water properties (heat, salt, nutrients, phytoplankton and dissolved oxygen). In earlier papers (Simpson et al., 1990, 1991; Nunes Vaz, 1990; Nunes Vaz & Simpson, 1994; Lund-Hansen et al., 1996) the ϕ concept based on the potential energy of the water column, was used as a tool to evaluate the parameters, which control the development and breakdown of stratification. However, most of this research was implemented in shelf sea areas dominated by strong tides, or in coastal areas with low to moderate freshwater flow. This paper attempts to quantify the mechanisms responsible for the vertical water density variations and the stratification – mixing incidents at the mouth of a dam – controlled river (Strymon river) in a semi-enclosed bay (Strymonikos Gulf, Northern Greece). The model was run under two different scenarios (the influence of Kerkini dam and the absence of Kerkini dam) to assess the impact of water retention on the stratification conditions at the river mouth.

2. STUDY AREA

Strymonikos Gulf is a semi-enclosed coastal water body in North Aegean Sea, having a surface area of 389.4 km^2 and a water capacity of 2.15×10^{10} m^3 (Figure 1). The area is considered among the most important nursery and fishing grounds of North Aegean Sea for pelagic species (Kallianiotis, 1999). Strymonikos Gulf is the final recipient for the catchments of River Strymon (drainage area: 18,329 km^2), which outflows on the northern part of the gulf with a mean annual discharge of 59.5 m^3 s^{-1}, supplying the gulf with freshwater and domestic, agricultural and industrial effluents (Koukouras et al., 1984; Vouvalidis, 1998; Parissis et al., 2001; Sylaios et al., 1999; Sylaios, 2002; Haralambidou et al., 2003, 2005).

The discharge pattern of Strymon River shows strong seasonal variability, ranging on the average from 18 m^3 s^{-1} in August to 122 m^3 s^{-1} in April (data before Kerkini Lake; Mertzanis, 1994). River flow and water quality of Strymon is closely associated with Kerkini Lake, a man-controlled artificial reservoir located 77 km upstream its mouth (Tryfon et al., 1996). To cover the great demand in irrigation water from the nearby agricultural fields, the lake's dam remains closed from July to September, thus diminishing river discharge from near zero to 20 m^3 s^{-1}. During recent decades a 30% reduction has been observed in the total freshwater input to the Gulf due to reduced precipitation and extensive irrigation within the drainage basin (Dounas and Koukouras, 1992). This leads to the intrusion of a salt wedge, which moves as far as 6-8 km upstream during low flow conditions (Parissis et al., 2001; Haralambidou et al., 2003).

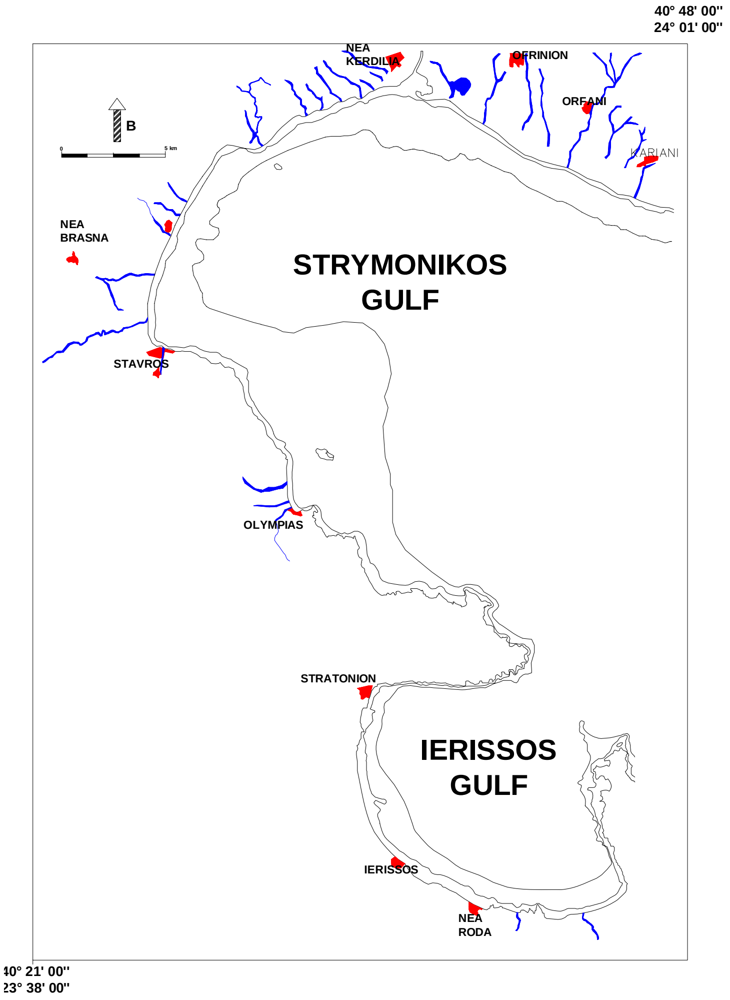

Figure 1. Map of Strymonikos Gulf.

3. METHODOLOGY AND DATASETS

The ϕ concept is based on the potential energy of the water column, since the fully mixed water column contains more potential energy than the stratified. The amount of energy required to obtain a fully-mixed water column (ϕ, J m^{-3}) is given by (Simpson & Bowers, 1981):

$$\phi = \frac{1}{h}\int_{-h}^{0} (\bar{\rho} - \rho)\, g\, z\, dz \ ; \ \bar{\rho} = \frac{1}{h}\int_{-h}^{0} \rho\, dz \tag{1}$$

where g is acceleration due to gravity (9.81 m s^{-2}), ρ is water density (kg m^{-3}), h is water column depth (m) and z is the vertical coordinate (m).

Mechanisms responsible for water column mixing are tidal stirring at the bottom and wind stirring at the surface. Tidal stirring on the bottom decreases ϕ by (Simpson & Hunter, 1974):

$$\left\{\frac{d\phi}{dt}\right\}_T = -\frac{\varepsilon\, k_b\, \rho_w \left|{u_b}^3\right|}{h} \tag{2}$$

where ε is an empirically determined coefficient of mixing (0.0038), k_b is a bottom drag coefficient (2.5 × 10^{-3}), ρ_w is water density (kg m^{-3}) and u_b is the bottom velocity (m s^{-1}).

Wind stirring at the surface decreases ϕ by:

$$\left\{\frac{d\phi}{dt}\right\}_W = -\frac{\delta\, k_S\, \rho_a \left|W^3\right|}{h} \tag{3}$$

where δ is a second empirically determined mixing coefficient (0.039), k_s is a surface drag coefficient (6.4 × 10^{-5}), ρ_α is the air density (1.2 kg m^{-3}) and W is the wind speed (m s^{-1}).

On the contrary, the stratifying mechanisms of the water column are the solar heating and the freshwater buoyancy flux. The solar heat flux at the sea surface increases ϕ by (Simpson & Bowers, 1981):

$$\left\{\frac{d\phi}{dt}\right\}_h = \frac{\alpha\, g\, Q}{2\, c_p} \tag{4}$$

where α and C_p are thermal expansion coefficients, with α = 1.6 × 10^{-4} ^{o}C^{-1} at 9^{o}C, C_p = 4.0 × 10^{3} J kg^{-1} ^{o}C^{-1} and Q is solar heat flux at the sea surface (W m^{-2}).

The freshwater buoyancy flux, and thus changes in ϕ induced by estuarine circulation, is given by (Nunes Vaz & Simpson, 1994):

$$\left\{\frac{d\phi}{dt}\right\}_R = \frac{1}{320}\,\frac{g^2 h^4}{N_Z\, \rho_W}\left(\frac{\partial\rho}{\partial x}\right)^2 \tag{5}$$

where h is the water depth (m) and N_Z is the vertical eddy viscosity coefficient (m^2 s^{-1}), varying with tidal amplitude as $N_Z = \gamma\, h\, u$, with γ = 3.3 × 10^{-3}, and u the depth mean tidal speed (m s^{-1}).

It occurs from the above that the stratification – mixing model of the water column considers that changes in time of the potential energy of the water column are due to wind mixing, heating, estuarine circulation and tidal currents, as follows:

$$\left\{\frac{d\phi}{dt}\right\}_{W,h,R,T}=-\delta k_S\,\rho_\alpha\left(\frac{W^3}{h}\right)+\frac{\alpha g Q}{2C_P}+\frac{1}{320}\frac{g^2h^4}{N_Z\,\rho}\left(\frac{\partial\rho}{\partial x}\right)^2-\varepsilon k_b\,\rho_W\left(\frac{\overline{u}^3}{h}\right) \tag{6}$$

In order to solve eq. (6) and derive the relative impact of each individual term in the change of the potential energy of the water column at the mouth of Strymon River estuary, we used: a) meteorological data sets (daily mean wind speed and daily mean solar heat flux for the year 2002, as provided by the NOAA ARL Real Time Environmental Application Internet site (http://www.arl.noaa.gov/ready/amet.html), b) mean monthly estimates of the ∂ρ/∂x-term, obtained by a series of CTD profiles at the mouth of Strymon River, under different river flow conditions (Haralambidou et al., 2004, Figure 2) , and c) daily mean values of tidal mean speed at the mouth of Strymon River, as obtained by a two-dimensional tidal numerical model of Strymonikos Gulf, which accounted for the fortnight variability under neap and spring tidal conditions (Sylaios, 2000). To assess the impact of water retention from Kerkini lake, we used the mean monthly values of Strymon river discharge during the period 1982-1993 (Hatzigiannakis, 1999), as recorded before Kerkini and after Kerkini river dam. Different river flows vary the density gradient at the mouth of Strymon River and influence the stratification conditions in the area.

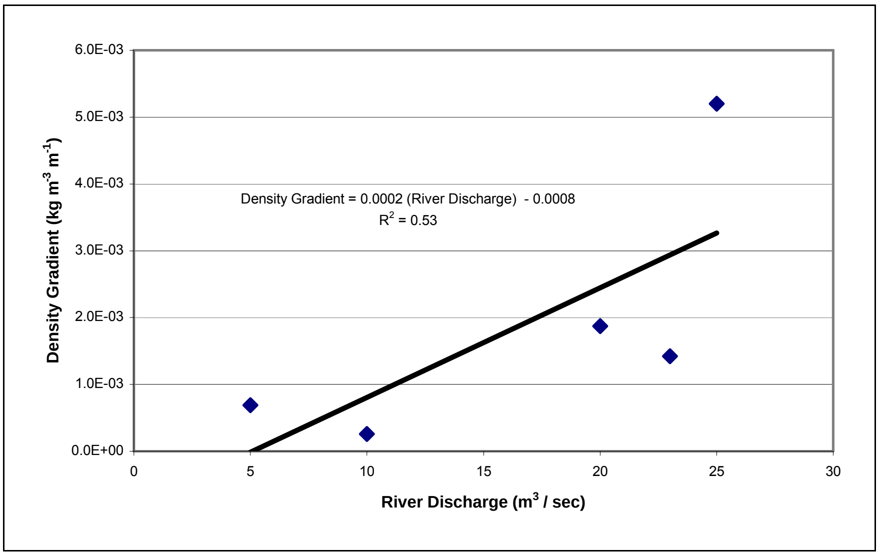

Figure 2. Density gradient variability, obtained from various CTD transects at the mouth of Strymon River, in relation to river discharge. Line of best fit (linear approximation) was used to estimate density gradient values under different river flow conditions.

Therefore, the time-interval within which the change of the potential energy in the water column was examined was 1 day, and thus eq. (6) was integrated with respect to time:

$$\phi_{TOTAL}=-\delta k_S\,\rho_a\left(\frac{1}{h}\right)\int_0^t W^3\,dt+\frac{\alpha g}{2C_p}\int_0^t Q\,dt+\frac{1}{320}\frac{g^2h^4}{N_Z\,\rho}\int_0^t\left(\frac{\partial\rho}{\partial x}\right)^2dt-\varepsilon k_b\,\rho_w\frac{1}{h}\int_0^t\overline{u}^3\,dt \tag{7}$$

4. RESULTS

Results concerning the mechanisms responsible for water column mixing are shown in Figure 3. Wind circulation in the area appears influenced by moderate to strong northerly winds during the winter, and southerly winds in the summer. Mean monthly water column potential energy (ϕ) due to wind influence was obtained daily from the first term of eq. (7). It occurs that the wind term has an annual mean value of 7.7 J m^{-3}, ranging between 1.4 J m^{-3} during October and 20.6 J m^{-3} during December (Figure 3b). Daily mean values of tidal current speed at the mouth of Strymon River are presented in Figure 3c, as provided by the M$_2$ tidal numerical model. The mean monthly values of water column potential energy (ϕ) due to tidal influence were computed from the fourth term of eq. (7), showing the almost constant mixing impact of tide (mean: 29.5 J m^{-3}) on the water column dynamics (Figure 3d).

The variability of the mechanisms responsible for water column stratification is shown in Figure 4. Incident solar radiation varies seasonally in the area from 48.50 W m^{-2} in December to 269.33 W m^{-2} in June (Figure 4a). This variability affects directly the water column stratification conditions at the mouth of Strymon River by inducing a seasonal thermocline. The produced ϕ - heat term, as obtained from the second term of eq. (7), ranges between 28.9 J m^{-3} in December and 152.8 J m^{-3} in July (Figure 4b).

Freshwater river discharge induces a buoyancy input in the area, which increases the horizontal density gradient and stratifies the water column. The monthly mean values of the density gradient at the mouth of Strymon River, as obtained by following the equation produced in Figure 2, show low values (2.0×10^{-4}) during the summer months (July to September), when freshwater input was limited due to the water retention by Kerkini dam. The horizontal density gradient term appeared higher (1.9×10^{-2}) during March and May, when the mean monthly freshwater discharge reaches a maximum (91.2 m^3 s^{-1} and 97.6 m^3 s^{-1} respectively). By considering river discharge as recorded before Kerkini Lake, we obtain higher density gradients (2.4×10^{-2}) in April, slightly increased summer values ($2.2–4.0 \times 10^{-3}$) and lower autumn and winter values ($5.4 – 8.4 \times 10^{-3}$; Figure 4c).

Water column potential energy (ϕ) shows a similar to density gradient behaviour under both conditions. Under the influence of Kerkini Lake, low values (0.01 J m^{-3}) during July and August and high values (70.9 J m^{-3}) in May were computed. The influence of water retention in stratification appears enhanced during spring and early summer (April to June), when water column potential energy is reduced by 59%, 14% and 15%, respectively (Figure 4d). In October the water retained in Kerkini dam is released, thus increasing the stratification of the coastal water column by approximately 50% (from 48.5 J m^{-3} without Kerkini Lake to 73 J m^{-3} with Kerkini dam).

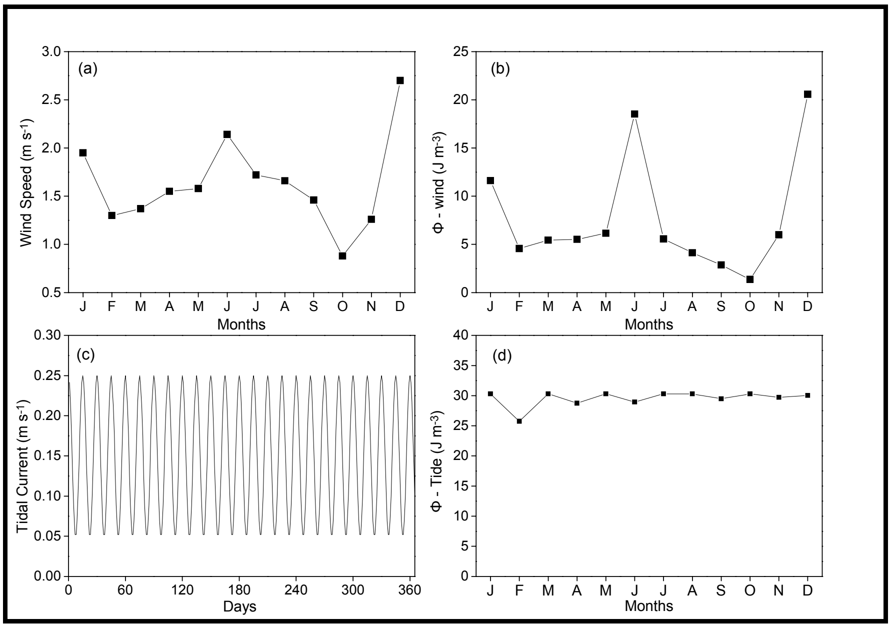

Figure 3. Variability of mechanisms responsible for water column mixing. (a) Mean monthly wind speed, (b) potential energy of water column (ϕ) due to wind influence, (c) daily mean tidal current speed, and (d) potential energy of water column (ϕ) due to tidal currents, at the mouth of Strymon River.

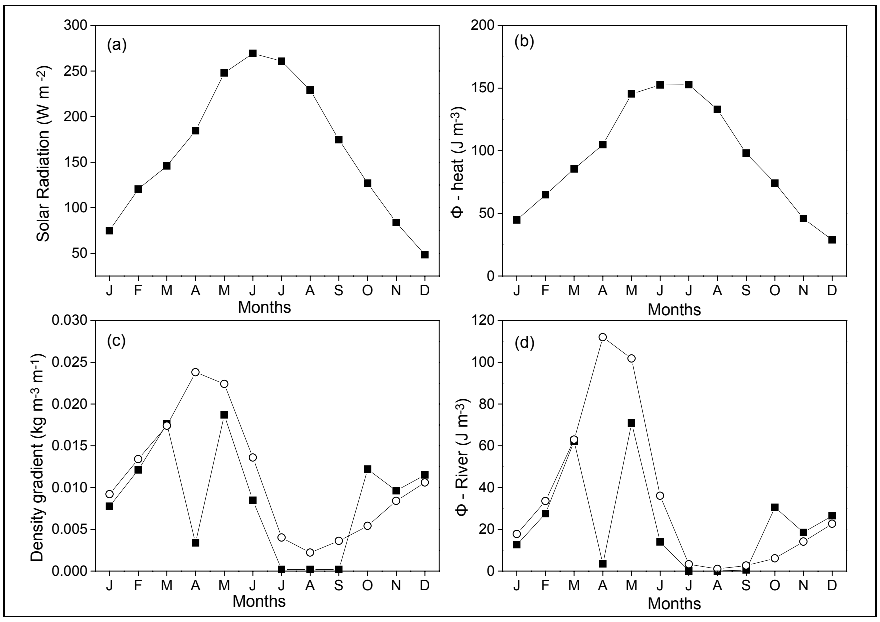

Figure 4. Variability of mechanisms responsible for water column stratification. (a) Mean monthly incident solar radiation, (b) potential energy of water column (ϕ) due to solar heat, (c) mean monthly density gradient (open circles: without Kerkini lake; solid squares: with Kerkini lake), and (d) potential energy of water column (ϕ) due to river discharge (open circles: without Kerkini lake; solid squares: with Kerkini lake), at the mouth of Strymon River.

Table 1 presents the average, maximum and minimum values of the potential energy of the water column (ϕ) for each term of equation (7) and the time of occurrence (month).

Table 1. Average, maximum and minimum values of the total potential energy of the water column (ϕ_T) and of the potential energy induced by solar insolation, wind, river discharge and tidal currents. Numbers in parenthesis represent the months of occurrence.

	ϕ_{TIDE} (J m^{-3})	ϕ_{WIND} (J m^{-3})	ϕ_{HEAT} (J m^{-3})	ϕ_{RIVER} (J m^{-3})	ϕ_{TOTAL} (J m^{-3})
			with Kerkini Lake		
Mean	-29.5	-7.7	94.2	22.2	72.9
Minimum	-25.7 (2)	-1.4 (10)	28.9 (12)	0.01 (7, 8)	4.8 (12)
Maximum	-30.3 (5)	-20.6 (12)	152.8 (7)	70.9 (5)	179.8 (5)
			without Kerkini Lake		
Mean				34.5	91.5
Minimum				1.02 (8)	0.9 (12)
Maximum				112.0 (4)	210.7 (5)

Figure 5 presents the temporal variability of (ϕ_{TOTAL}) – term under both scenarios, within a typical year, as obtained by solving eq. (7). A gradual increase of water column potential energy, and therefore water column stratification conditions, from January to March, induced by the freshwater input of Strymon River (mean discharge 67 m^3 s^{-1}). When Kerkini lake is considered, mean monthly river discharge reduces in April to 21 m^3 s^{-1} and the (ϕ_{TOTAL}) – term decreases to the level of 73.9 J m^{-3}. During the summer (May to August), enhanced stratification conditions of the water column prevail (ϕ_{TOTAL} from 98 to 180 J m^{-3}), due to the influence of solar heat (ϕ_{HEAT} from 130 to 150 J m^{-3}). During the same period, the stratifying influence of river input reduces rapidly from 70.9 to 0.01 J m^{-3}, since freshwater discharge diminishes to a minimum flow of 5 m^3 s^{-1} at the mouth of Strymon River. From September to December the potential energy of the water column at the mouth of Strymon River decreases gradually, since the mixing mechanisms of the wind and tide obtain maximum values. In December, the (ϕ_{TOTAL}) – term obtains the minimum value (4.8 J m^{-3}), due to increased mixing induced by the wind shear stress. Figure 5 also presents the stratification conditions at the mouth of Strymon River when Kerkini lake is absent. Increased stratification conditions during spring and early summer period (April to June) are shown, producing a mean annual increase in the (ϕ_{TOTAL}) – term of the order of 13%.

5. CONCLUSIONS

A stratification – mixing model, in terms of the potential energy of the water column (ϕ) has been developed and applied in Strymon River mouth. The model intents to assess the influence of water retention by a man-controlled artificial reservoir (Kerkini lake) on the stratification conditions at the mouth of Strymon River. The model accounts separately the effects of wind, solar heating, tidal circulation and river flow on the stratification – mixing conditions in the shelf zone. The model utilizes field data (CTD transects at the mouth of Strymon River), historical data of river discharge, wind and solar heat, and results of a tidal numerical model of the area. Results show that water retention by Kerkini lake plays an important role in the water column stratification conditions at the mouth of Strymon River during spring and early summer period (April to June), by reducing the mean annual water column potential energy (ϕ_{TOTAL}) by approximately 13% (from 79.2 J m^{-3} to 91.5 J m^{-3}).

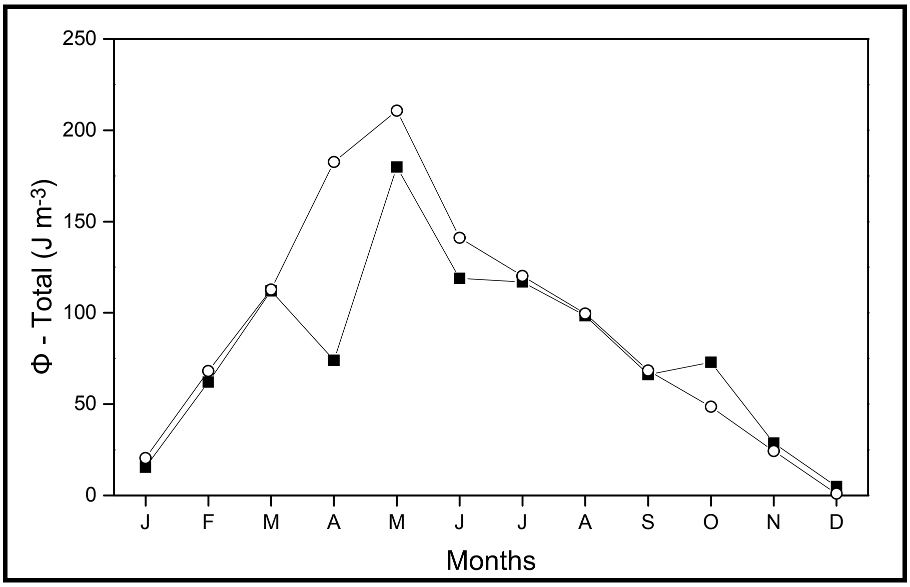

Figure 5. Variability of the total potential energy of the water column (ϕ_{TOTAL}), throughout a typical year, at the mouth of Strymon River (open circles: without Kerkini lake; solid squares: with Kerkini lake).

REFERENCES

Dounas C., Koukouras A.: 1992, Circalittoral macrobenthic assemblages of Strymonikos Gulf (North Aegean Sea). Mar Ecol; 13: 85-99.

Haralambidou K., Sylaios G., Tsihrintzis V.A.: 2003, Development of a numerical model to test alternatives to control saline wedge intrusion in an estuary. Proc. XXIII IAHR Congress; August 24-29; Thessaloniki, Greece, Theme A, pp. 107-112 .

Haralambidou, K., Tsihrintzis, V.A., Sylaios, G.: 2003, Testing alternatives for salt wedge management in an estuary with the use of monitoring and a mathematical model. Global Nest: An Intern. Journal; 5:105-116.

Haralambidou K., Tsihrintzis V.A., Sylaios G.K., Akratos C.: 2004, Seasonal and spatial characteristics of water quality in the estuary of Strymon River. Proc. of 7th Int. Conf. on Protection and Restoration of the Environment, 28/6 – 1/7/2004, Mykonos, Greece, CD-ROM, Section 3, No. 3.

Haralambidou, K., Tsihrintzis, V.A., Sylaios, G.K., Akratos, C.: 2005, Seasonal and spatial characteristics of water quality in the estuary of Strymon River. J. Marine Environm. Engin.;7(4): 231-239.

Hatzigiannakis S.: 1999. "Hydrology of the Strymon River drainage basin", In *Description of the Coastal Zone of Strymonikos and Ierissos Gulfs*, Koutrakis E., Lazaridou E., (Eds.), NAGREF-GBWC, Kavala, pp. 5-32.

Kallianiotis A.: 1999, The anchovy fishery in the Aegean Sea. A flourishing industry or a lost affair?. Scient. Mar.; 60 (Suppl. 2): 287-288.

Koukouras A., Voultsiadou-Koukouras E., Kattoulas M. : 1984, Benthic bionomy of the North Aegean Sea. I. Physico-chemical characteristics of the Strymonikos Gulf. Thal. Jucosl.; 20: 53-72.

Lund-Hansen L.C., Skyum P., Christiansen C.: 1996, Modes of stratification in a semi-enclosed bay at the North sea-Baltic sea transition. Est., Coast. & Shelf Sci.; 42: 45-54.

Mertzanis C.: 1994, Study of flooding waves at Strymon River, M.Sc. Thesis, Univ. of Thessaloniki, 88 p., (in Greek).

Nunes Vaz R.A.: 1990, "Periodic stratification in coastal waters", In *Modeling of Marine Systems*, vol. 2, A.M. Davies, ed., pp. 69-105, CRC Press: Boca Raton, Fla.

Nunes Vaz R.A., Simpson J.H. : 1994, Turbulence closure modeling of estuarine stratification. J. Geoph. Res.; 99(C8): 16143-16160.

Parissis A., Sylaios G., Tsihrintzis V.A. : 2001, A numerical model for the study of salt intrusion at Strymon River mouth, Northern Greece. Proc. 1st Int. Cong. on Ecol. Prot. of Planet Earth; June 5-8, Xanthi, Greece, pp. 281-288.

Simpson J.H., Hunter J.R.: 1974, Fronts in the Irish Sea. Nature; 250:404-406.

Simpson J.H., Bowers D.G.: 1981, Models of stratification and frontal movement in shelf seas. Deep Sea Res.; 28:727-738.

Simpson J.H., Brown J., Matthews J., Allen, G.: 1990, Tidal straining, density currents, and stirring in the control of estuarine stratification. Estuaries; 13: 125-132.

Simpson J.H., Sharples J., Rippeth, T.P.: 1991, A prescriptive model of stratification induced by freshwater runoff. Est., Coast. & Shelf Sci.; 33: 23-35.

Sylaios G., Ioannidou D., Koutrakis E.: 1999, "Water quality monitoring in Strymonikos gulf and gulf of Ierissos, N. Greece", In *Water Pollution V*, Brebbia, C.A., Anagnostopoulos, P., (Eds.), WIT Press, Southampton, pp. 303-310.

Sylaios G.: 2000, A numerical model of coastal circulation and pollutants dispersion in Strymonikos Gulf. Proc. of 6th Panhell. Congr. in Ocean. & Fish., 23-26/5/2000, Chios, pp. 546-548.

Sylaios G.: 2002, A budget model of water, salt and non-conservative nutrients in Strymonikos and Ierissos Gulfs. Proc. of the 5th Int. Conf. of EWRA; 2002 September 4 – September 8, Athens, pp. 502 – 510.

Tryfon E., Moustaka-Gouni M., Nikolaidis G.: 1996, Phytoplankton and nutrients in the River Strymon, Greece. Int. Revue ges. Hydrobiol ; 81 : 281-292.

Vouvalidis K.: 1998, Morphologic, sedimentary and oceanographic processes and human interventions contributing to the evolution of Strymon River estuarine system, Ph.D. Thesis, Univ. of Thesaloniki, 198 p. (in Greek).