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Hydrographic variability, nutrient distribution and water mass dynamics in Strymonikos Gulf (Northern Greece)

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Abstract

Four seasonal hydrographic sampling cruises, covering a grid of 36 stations, were organized in the area of Strymonikos and Ierissos Gulfs, in Northern Greece, during 1997–1998. The aim of the study was to provide insight into the spatial and seasonal variability of physical and chemical oceanographic parameters, to define the baroclinic circulation, and to describe the dynamics of Strymon River plume area and the related freshwater and nutrient transport processes. Results, in all cruises, indicated the relatively limited contribution of river inputs, the strong influence of Black Sea Water (BSW) in the gulf's hydrography, and the summer intrusion of Levantine Intermediate Water in the outer Strymonikos Gulf. The baroclinic circulation (5/40 dbar) revealed the presence of mesoscale and smaller-scale features (meanders, frontal zones and eddies), associated with Strymon and Richios River discharges. Freshwater input covered the surface nearshore zone of Strymonikos Gulf, classifying the area as a 'wide shelf' region. The total freshwater content in the gulf was calculated to vary from 12.6×10^6 to $65.8 \times 10^6\,m^3$ in the summer and winter period, respectively. This variability leads to a freshwater residence time ranging between 5 and 48 days, according to the Strymon River flow conditions. A distinct nutrient gradient was observed between freshwater inflow, the mixed plume zone and the remaining Strymonikos Gulf. Dissolved inorganic nitrogen (DIN) and phosphorus (DIP) concentrations followed opposite temporal variability patterns, with DIN being exhausted in the summer and increased in the winter. DIN:DIP ratios illustrate that the system appears shifting from a winter phosphorus limitation to a summer nitrogen limitation behavior.

Keywords: Hydrography; River plume; Seasonal variation; Water mass; Nutrients; Strymonikos Gulf; Mediterranean Sea

1. Introduction

The continental coastal zone of the North Aegean Sea is of considerable socio-economic importance for Greece, since it supports commercial fishing industry and large-scale tourism. Hydrology in the area is mostly influenced by a number of external factors, such as the largely variable inflow of cooler and fresher Black Sea Water (BSW), its mixing with the more saline Levantine Intermediate Water (LIW) and the presence of an extended continental shelf and an irregular bottom topography (Yuce, 1995; Poulos et al., 1997). BSW forms a strong surface current flowing through the Dardanelles with an average speed of approximately $0.60\,m\,s^{-1}$, moving cyclonically along the Thracian Sea (Bethoux, 1980; Malanotte-Rizzoli and Hecht, 1988), advancing into Kavala and Strymonikos

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Gulfs (Kaloumenos, 1984; Sylaios et al., 1999; Barbopoulos et al., 2000). Furthermore, surface water mass properties are also affected by significant buoyant water discharge at the vicinity of the estuaries of Rivers Evros, Nestos and Strymon.

Strymonikos Gulf (surface 389.4 km^2, volume $2.15 \times 10^{10}\,m^3$) and Ierissos Gulf (surface 166 km^2, volume $8.30 \times 10^{9}\,m^3$) are two of the larger semi-enclosed water bodies in the Thracian Sea, considered among the most important nursery and fishing grounds of North Aegean Sea for pelagic species (Kallianiotis, 1999) (Fig. 1). Isobaths in Strymonikos Gulf increase rapidly away from the coast, reaching 40 m of depth within 2 km from shore, until a maximum depth of 90 m at the nearly flat central part. Exchange between the gulf and the open North Aegean Sea occurs through the eastern open boundary, being 30 km long and 90 m deep in an N–S direction. Ierissos Gulf has a similar bathymetric pattern, with a maximum depth of 80 m located at the northeastern part of the gulf. This gulf is connected with the outer part of Strymonikos Gulf, through a 10 km long opening.

Strymonikos Gulf is the final recipient for the catchments of Strymon River (drainage area: 18,329 km^2) and Richios River (drainage area: 2090 km^2), together with smaller basins scattered along the coastal zone (drainage area: 598 km^2) (Hatzigiannakis, 1999). Strymon River drains populated and agricultural areas and outflows at the northern part of the gulf with a mean annual discharge of 59.5 $m^3\,s^{-1}$ (Koukouras et al., 1984; Vouvalidis, 1998). 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 (Mertzanis, 1994). River flow and water quality of Strymon is closely associated with Kerkini Lake, a man-controlled artificial reservoir, located 77 km upstream of its mouth (Tryfon et al., 1996). To cover the great demand in irrigation water for the nearby agricultural fields, the Kerkini Dam remains closed from March to September, thus diminishing river discharge from near zero to 20 $m^3\,s^{-1}$. In 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; Hatzigiannakis, 1999) (Fig. 2). This leads to the intrusion of a salt wedge, which moves as far as 7 km upstream during low flow conditions (Parissis et al., 2001; Haralambidou et al., 2005). Richios River, with a mean annual discharge of 0.90 $m^3\,s^{-1}$, remaining relatively constant throughout the year, transports freshwater from Volvi Lake to the western part of this coastal area. Moreover, a number of seasonal streams and torrents outflow in Strymonikos Gulf, having average annual flows of 1.70 $m^3\,s^{-1}$ (Hatzigiannakis, 1999).

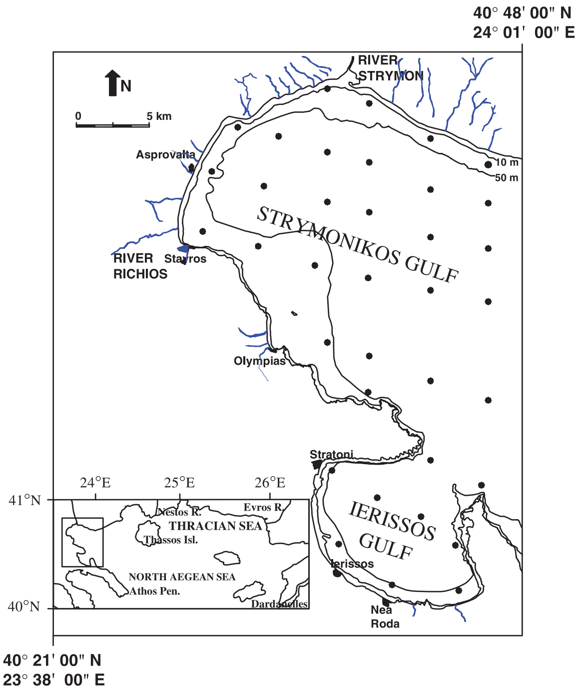

Fig. 1. Map of the study area showing the CTD and nutrients sampling grid. The map also shows the bottom topography (isobaths of 10 and 50 m), the land hydrographic network and the location of major coastal communities.

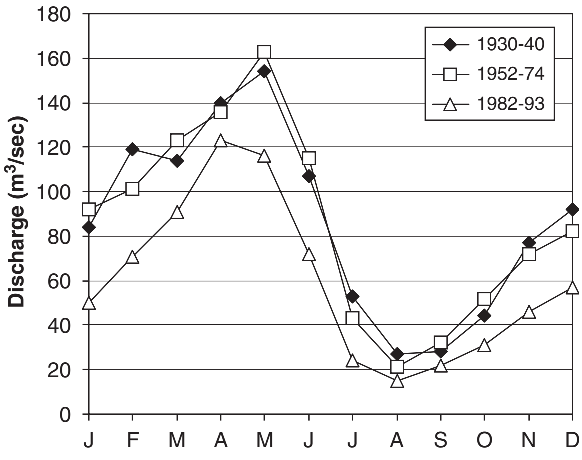

Fig. 2. Mean monthly variation of Strymon River discharge, during different periods (after Hatzigiannakis, 1999).

The climate of this typical Mediterranean basin is strongly influenced by seasonality (Mariopoulos, 1982), dominated by moderate precipitation, cold winter and arid summer periods. Mean annual evaporation (968.2 mm during 1984–1994) exceeds mean annual precipitation (644 mm for the same period), producing a net water deficit (Hatzigiannakis, 1999). This budget appears affected by seasonality, being usually negative from the summer to the end of the winter and slightly positive in the spring. However, since river annual discharge ($\sim 19.6 \times 10^8\,m^3$) appears about 10 times higher than the net loss of water to the atmosphere ($V_P - V_E \sim -1.6 \times 10^8\,m^3$), an annual water surplus is produced of about $18 \times 10^8\,m^3$, classifying Strymonikos Gulf as a pure dilution-type basin. The broader area is characterized by weak tides with tidal amplitude varying between 0.45 m during spring tides and 0.20 m during neap tides (Sylaios et al., 1999).

Freshwater flow can have a significant impact on the water circulation, mixing and dynamics of such micro-tidal, semi-enclosed estuaries and the adjacent continental shelf (Wong, 1999; Hyder et al., 2002; Salat et al., 2002). Furthermore, riverine freshwater volume is associated with significant nutrient loads to the estuary, strongly dependent on the levels of river flow, sewage discharge, local agriculture and industrial activity of the whole drainage basin (Balls, 1992; Sanders et al., 1997; Sierra et al., 2002). In this paper, we attempt to analyze the distribution of hydrographic properties (temperature, salinity and nutrients) in Strymonikos and Ierissos Gulfs on a seasonal basis, estimate the freshwater content supplied from river runoff and utilize the existing density anomalies to define the baroclinic circulation within the gulf. Moreover, the dynamics governing the river plume area and the related transport and distribution of nutrients in the water column of these two semi-enclosed gulfs are examined.

2. Materials and methods

2.1. Data collection

Hydrographic field data in 36 stations (28 in Strymonikos and eight in Ierissos Gulf) were collected during four seasonal monitoring periods (6–8 June, 15–18 September, 12–14 November 1997 and 20–22 February 1998). The sampling time periods were selected to cover the dam-controlled Strymon River flow period (June), the gulf's response to the dam opening (September) and the periods of gradually increased river flow (November and February). Conductivity–temperature–pressure (CTD) hydrocasts were undertaken onboard the R./V. *C. Paraschos* using an Idronaut 301 probe. CTD data were processed concerning misalignment corrections due to different response time of sensors, producing a 1 m vertical resolution for the processed profiles. Navigation was carried out using the Global Positioning System. Fig. 1 presents the hydrographic sampling grid, characterized by an average station spacing of 4.6 km covering both shallow and deep water, the larger coastal communities and the detailed hydrographic network of this coastal zone.

Water samples were collected at 1, 10, 20, 30, 40 and 50 m depth, at each sampling station, using a Van Dorn 1.21 sampler. Dissolved oxygen was determined using an automated Winkler system based on the design of Friederich et al. (1991). Dissolved nutrient concentrations (nitrates, nitrites, phosphates and silicates) were measured following the techniques reported by Parsons et al. (1984), using a Beckman DU 65 spectrophotometer. Ammonia was determined following the fluorometric method described by Liddicoat et al. (1974). Quality control for nutrient determination showed that precision of all analyses was better than 5% (0.05 μM for nitrates, 0.04 μM for phosphates and 0.2 μM for silicates).

Meteorological (air temperature, barometric pressure, precipitation, wind speed and direction) and tidal data during the week prior to each sampling period were obtained from a self-recording station positioned at Kavala harbor (30 km east of the study area), the closest operating station during the study period. Comparison of these data with those obtained from a mobile station installed in situ during days at sea, showed an error of $\pm 1\,m\,s^{-1}$ in wind speed and $\pm 0.5\,^{\circ}C$ in air temperature. Strymon River discharge was approximated using the Kerkini Lake Dam Authority mean daily flow rates. Season-dependent estimates of downstream volume losses for irrigation accounted an average reduction of 5% in the total freshwater input, during the spring and summer period.

2.2. Data processing

Water density was computed by the new international equation of state for seawater following the UNESCO algorithms (Fofonoff and Millard, 1983;

Fofonoff, 1985). The spatial anomalies in the potential energy of the water column resulting from differences in the density field were described using relative topography maps at 5 dbar relative to the reference level of 40 dbar. The calculated geostrophic velocity error due to CTD sensors performance was derived from the instrument's pre-cruise and post-cruise calibration parameters. CTD measurement errors were as follows: 0.01 °C in temperature, 0.5 dbar in pressure and 0.01 mS cm^{-1} in conductivity. Thus, methodological uncertainties in calculated geostrophic velocity due to only CTD sensor accuracy lie in the range of $\pm$0.04 m s^{-1} at a pressure level of 5 dbar, as referred to 40 dbar.

Based on the recorded salinity distribution, the seasonal variability of the total freshwater volume V_f, of each gulf area was derived through the salinity deficit method. Since BSW modifies seasonally the mean system's salinity, a reference salinity level (S_o) was considered for each sampling period as appropriate to describe the seawater free from any freshwater influence. The produced salinity deficit for each depth cell ($\Delta z = 1$ m) and grid cell ($\Delta A = 1.88 \times 10^7$ m^2) was then integrated vertically and horizontally to provide the total gulf's freshwater volume V_f as follows:

$$V_f = \sum_{x=1}^{m} \sum_{z=1}^{n} \frac{(S_o - S)}{S_o} \Delta A \Delta z, \qquad (1)$$

where S is the salinity of each depth and grid cell, as obtained from the closest CTD profile, n the maximum depth of each grid cell and m the total number of cells in the spatial grid covering the area. Then, the river water residence time t was estimated as

$$t = \frac{V_f}{Q}, \qquad (2)$$

where Q is the river discharge. Although these estimates of freshwater content and residence time are crude, due to the low resolution of the station grid, especially at the plume area, they may provide an indication on the magnitude and seasonal variability of these parameters in Strymonikos Gulf.

3. Results

3.1. Water masses variability

The seasonal $T-S$ diagrams (Fig. 3) show the presence of three water types: river plume water (RPW), BSW and LIW. The strong seasonality in the contribution of river input (RPW) is evident from these graphs, which is limited to a surface layer varying from 1 m (September 1997) to 4 m (February 1998). The Black Sea originated layer (BSW) occupies the remaining water of the column during all seasons ($\sigma_t = 24.5-28$ in June and November, $\sigma_t = 22-28$ in September, $\sigma_t = 25.2-28$ in February). However, in the summer (June 1997) this layer appeared thinner (up to 55 m), thus allowing the entry of the LIW ($\sigma_t = 29$) in the deeper parts of the outer gulf. With these diagrams, the reference salinity S_o for the freshwater content calculation in each sampling period was determined as the higher RPW value (Table 1).

3.2. Vertical dynamics

Water column stratification is closely related to the surface heating cycle and the buoyancy input, as displayed from the typical seasonal profiles of temperature, salinity and density (σ_t) in Strymonikos and Ierissos Gulfs (Fig. 4). In June, the freshwater forms a surface layer, 2 m deep near river mouths ($T = 19.3$ °C; $S = 27.8$), superimposed on an intermediate layer (2–20 m) defined by the seasonal thermocline ($T = 12.9$ °C; $S = 37.7$). A bottom water mass occupies depths higher than 20 m characterized by a slight temperature and salinity increase ($T = 14.2$ °C; $S = 38.8$). In September, the thermocline at 20–25 m depth increases stratification, separating a surface well-mixed layer ($T = 22.5$ °C; $S = 29.4$) and a bottom water mass ($T = 14.6$ °C; $S = 37.8$). In November, the water column was characterized by a gradual salinity increase and nearly constant temperature conditions ($T = 16.0$ °C; $S = 31.0$ at surface, $T = 17.4$ °C; $S = 37.4$ at mid-depth and $T = 15.0$ °C; $S = 37.8$ at the bottom). A two-layer system consisting of a fresh and cold surface water mass ($T = 10.8$ °C; $S = 22.7$) and a warm and saline bottom water mass ($T = 15.2$ °C; $S = 37.2$) were observed in February.

3.3. Surface variability

River Richios discharges warmer and fresher water ($T = 20.9-22.0$ °C; $S = 28.8-30.0$; $\sigma_t = 19.8-22.5$) than that of River Strymon ($T = 19.5-20.0$ °C; $S = 29.4-31.0$; $\sigma_t = 18.8-22.8$). The rest of the study area is characterized by colder and saltier water masses ($T = 19.3-19.6$ °C; $S = 35.0-35.5$; $\sigma_t = 24.0-25.6$) (Fig. 5). Geostrophic

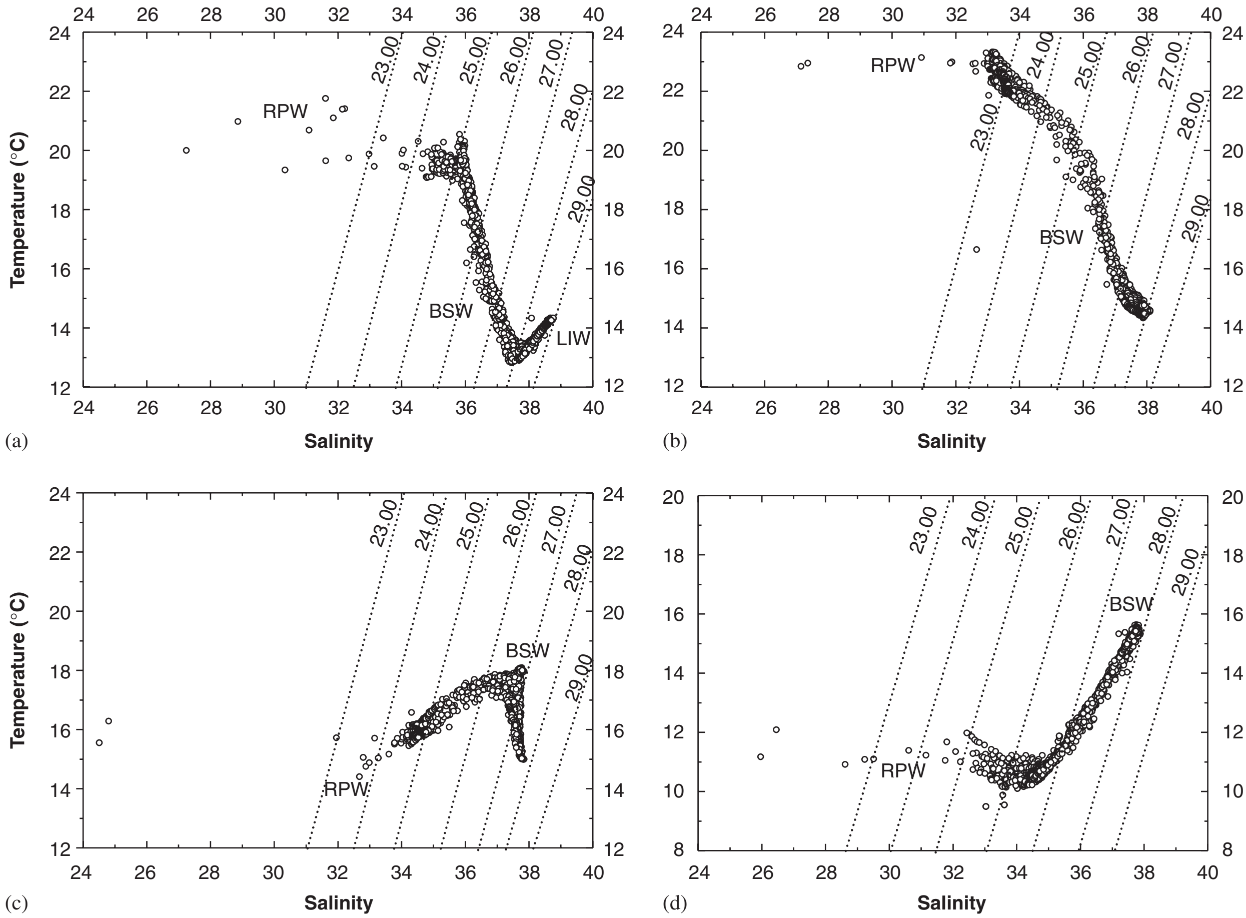

Fig. 3. $T-S$ diagrams for water mass identification in Strymonikos and Ierissos Gulfs, as measured at CTD stations, during (a) June 1997, (b) September 1997, (c) November 1997 and (d) February 1998. Dashed lines indicate σ_t lines.

Table 1
Summary of key physical parameters of Strymonikos Gulf during the four sampling cruises

	June 1997	September 1997	November 1997	February 1998
Sea surface temperature (°C)	19.82	22.57	15.69	10.88
Sea surface salinity	33.58	32.71	34.10	33.00
Sea surface density (σ_t)	23.73	22.32	25.12	25.24
Mean Gulf's temperature (°C)	15.91	17.45	16.37	13.17
Mean Gulf's salinity	36.93	36.24	36.26	36.29
Mean Gulf's density (σ_t)	27.23	26.32	26.63	27.33
Strymon River discharge ($m^3 s^{-1}$)	12.5	3	43	147
Reference salinity	34.5	33.0	34.5	34.5
Freshwater volume ($10^6 m^3$)	26.2	12.6	33.6	65.8
Freshwater surface coverage (km^2)	218	128	170	300
Freshwater residence time (d)	24.3	48.6	9.0	5.2
Freshwater surface elevation (m)	0.12	0.09	0.19	0.21

circulation at the outer Strymonikos Gulf shows clearly a frontal system with a north–south direction and a southward flow into Ierissos Gulf and out of Strymonikos Gulf. At the inner gulf an anti-cyclonic eddy system with a 7.5 km diameter is being defined by the maximum geopotential heights.

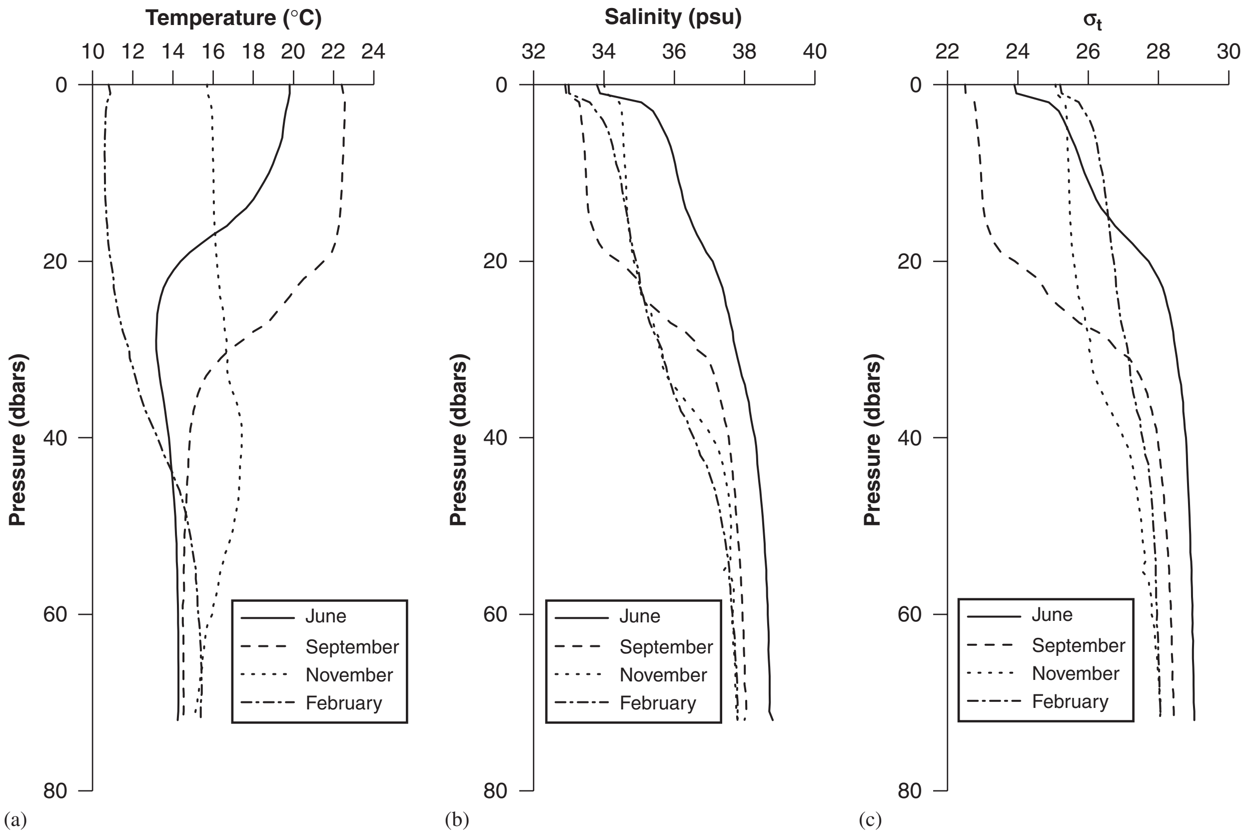

Fig. 4. Typical profiles of (a) temperature, (b) salinity and (c) density σ_t in Strymonikos and Ierissos Gulfs, during the four sampling periods.

In September, the regions of freshwater influence appear well determined at the mouths of both river systems. The 23 °C isotherm defines the influence of River Strymon ($T = 22.6-22.9$ °C; $S = 27.3-29.1$; $\sigma_t = 18.2-20.8$), while seawater masses are colder ($T = 22.1-22.5$ °C; $S = 33.0-33.7$; $\sigma_t = 22.4-23.2$) and horizontally homogeneous (Fig. 6). Dynamic height distribution shows the occurrence of a frontal system, separating an anti-cyclonic eddy at the boundary of the gulf and a strong cyclonic flow at the inner southwestern part of the gulf.

Low surface water temperature, ranging between 15.0 and 15.4 °C, appears in November 1997 (Fig. 7) at the coastal zone of Stavros, Asprovalta and the estuarine system of Strymon River, due to the outflow of cold water masses from Rivers Strymon and Richios. The remaining water masses in Strymonikos and Ierissos Gulfs appear warmer (15.8–16.0 °C). The surface salinity field shows freshwater masses ($S = 31.5-32.0$) originating from Richios River, moving toward the center of the gulf, where horizontally homogeneous conditions exist. Similar homogeneity is observed at the surface distribution of density, with σ_t ranging between 25.0 and 25.2. Dynamic topography at 5 dbar (/40 dbar) shows an anti-cyclonic eddy at southeastern boundary of Strymonikos Gulf, having a 6 km diameter, and a cyclonic eddy, with a 12 km diameter, at the coastal zone of Olympias and Asprovalta, following the freshwater outflow of Richios River.

In February 1998 (Fig. 8), surface temperature distribution is mostly determined by the cooler surface water drainage at the area between Olympias and Stratoni (9.0–9.5 °C), while warmer horizontally homogeneous conditions prevail at the rest of the study area (11–12 °C). The salinity distribution presents the significant influence of Strymon River ($S = 22.0-23.5$) under increased discharge conditions, creating intense local gradients at the coastal zone between Asprovalta and Ierissos. Horizontal homogeneity prevails at the rest of Strymonikos and Ierissos Gulfs ($S = 33.0-34.5$). Geostrophic flow transports water out of Strymonikos

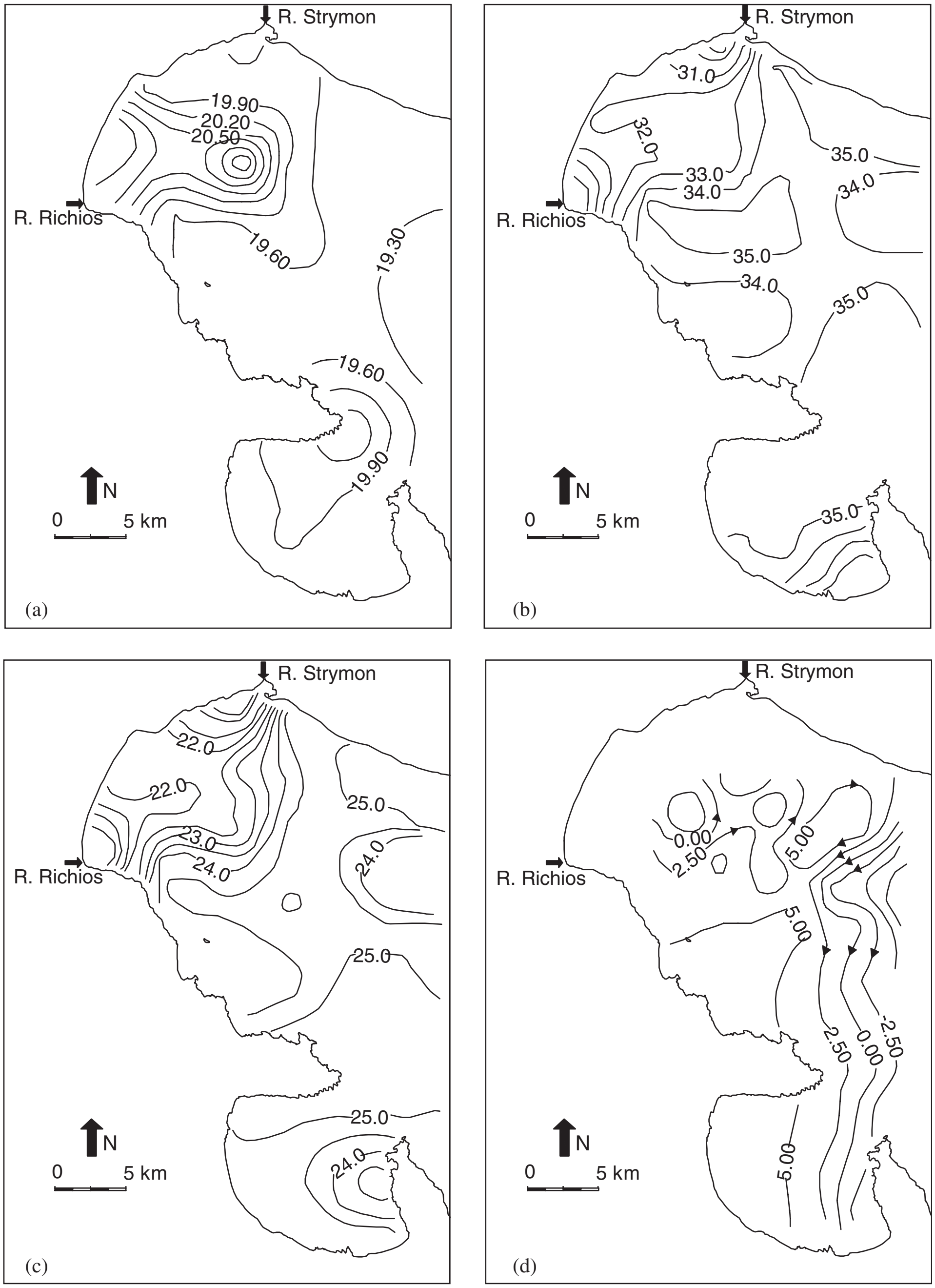

Fig. 5. Spatial distribution of (a) temperature (in °C), (b) salinity, (c) density σ_t and (d) dynamic height anomaly (in mm for 5/40 dbar), at the surface of Strymonikos and Ierissos Gulfs, during 6–8 June 1997.

Gulf, while the southeastern anti-cyclonic eddy persists at its outer boundary.

3.4. Nutrients variability and mixing patterns

Nutrients concentrations measured in Strymonikos and Ierissos Gulfs showed significant spatial and temporal variability. Dissolved inorganic nitrogen (DIN) concentrations (nitrate, nitrite and ammonium) of Strymonikos Gulf were found higher during the November (1.78 μM) and February (3.45 μM) cruises, showing summertime declines (1.42 μM in June 1997 and 1.62 μM in September 1997). Dissolved inorganic phosphorus (DIP)

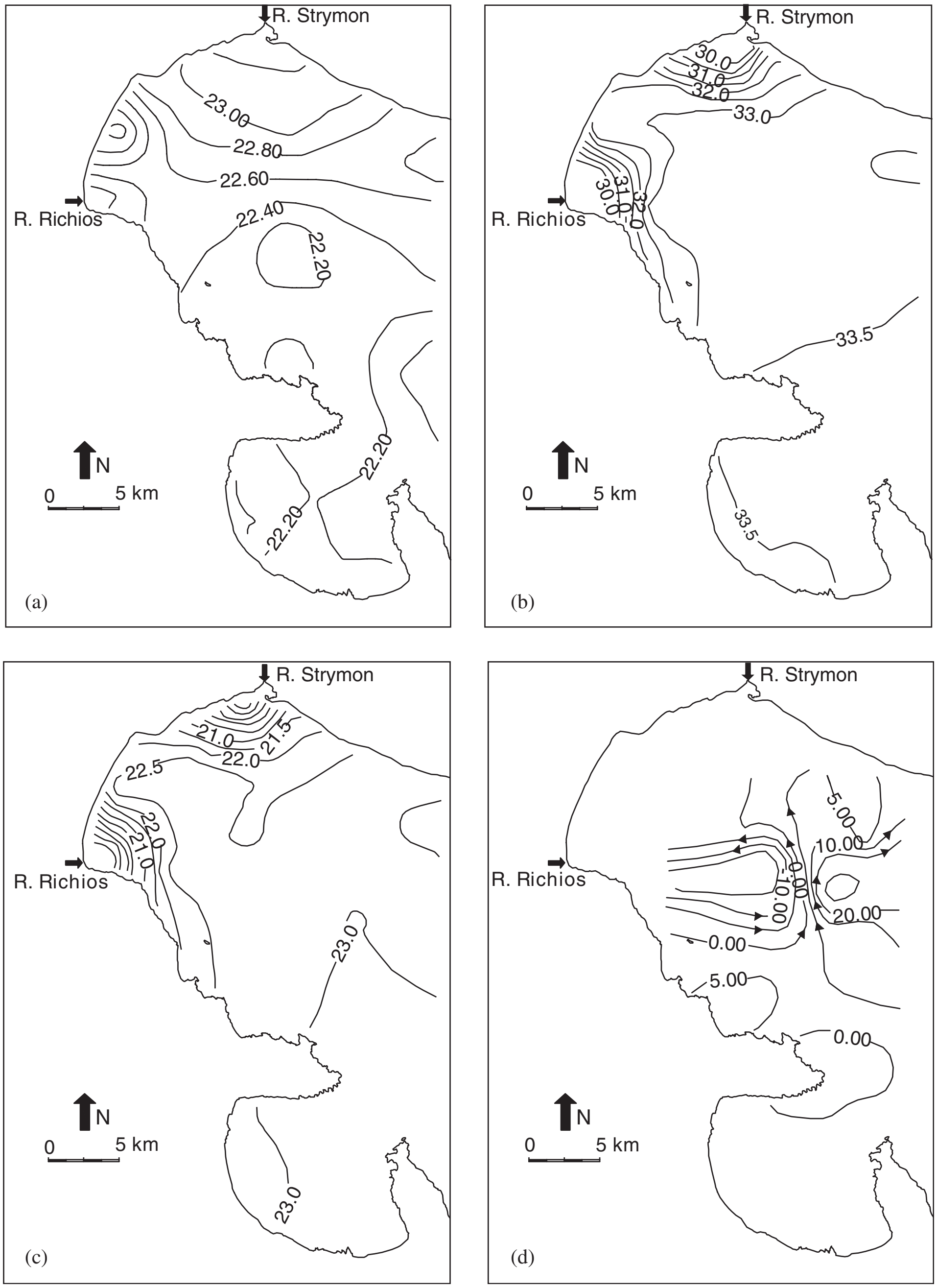

Fig. 6. Spatial distribution of (a) temperature (in °C), (b) salinity, (c) density σ_t and (d) dynamic height anomaly (in mm for 5/40 dbar), at the surface of Strymonikos and Ierissos Gulfs, during 15–18 September 1997.

concentrations presented an opposite behavior with increased summer values (0.66 μM) in June 1997, descending in the winter to 0.18 and 0.14 μM in November and February, respectively. The surface distributions of DIN and DIP are shown in Fig. 9.

Concerning the vertical variability, higher values were observed in all seasons at the surface layer of the station located in the immediate vicinity of Strymon River mouth. Fig. 10 illustrates typical profiles of nutrient concentrations in the study area. Surface nitrate concentrations ranged between

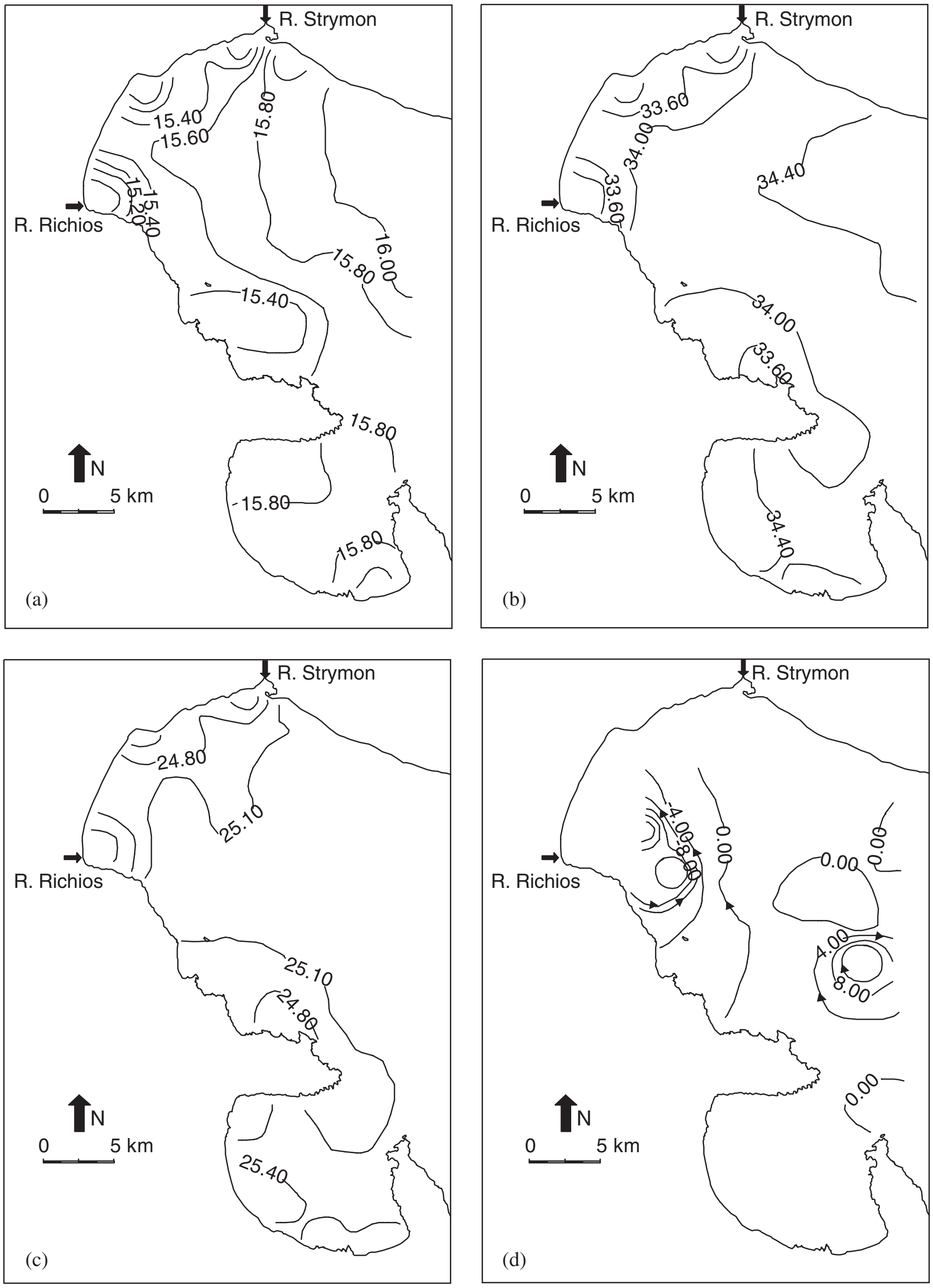

Fig. 7. Spatial distribution of (a) temperature (in °C), (b) salinity, (c) density σ_t and (d) dynamic height anomaly (in mm for 5/40 dbar), at the surface of Strymonikos and Ierissos Gulfs, during 12–14 November 1997.

8.72 μM in February and 0.30 μM in September, with a general trend to decrease with depth and to show local intermediate peaks. Nitrites showed a gradual increase with depth (0.07 μM at the surface to 0.28 μM at the bottom) and reduced temporal variability. The vertically homogeneous ammonium profiles were characterized by important seasonal variability (0.25 μM in June to 0.79 μM in November and February). On the contrary, a typical profile of phosphate concentration presented increased surface and bottom values in the summer period (1.20 μM in June to 0.18 μM in February). Important seasonal variability was depicted at the surface silicate concentration, with higher values being

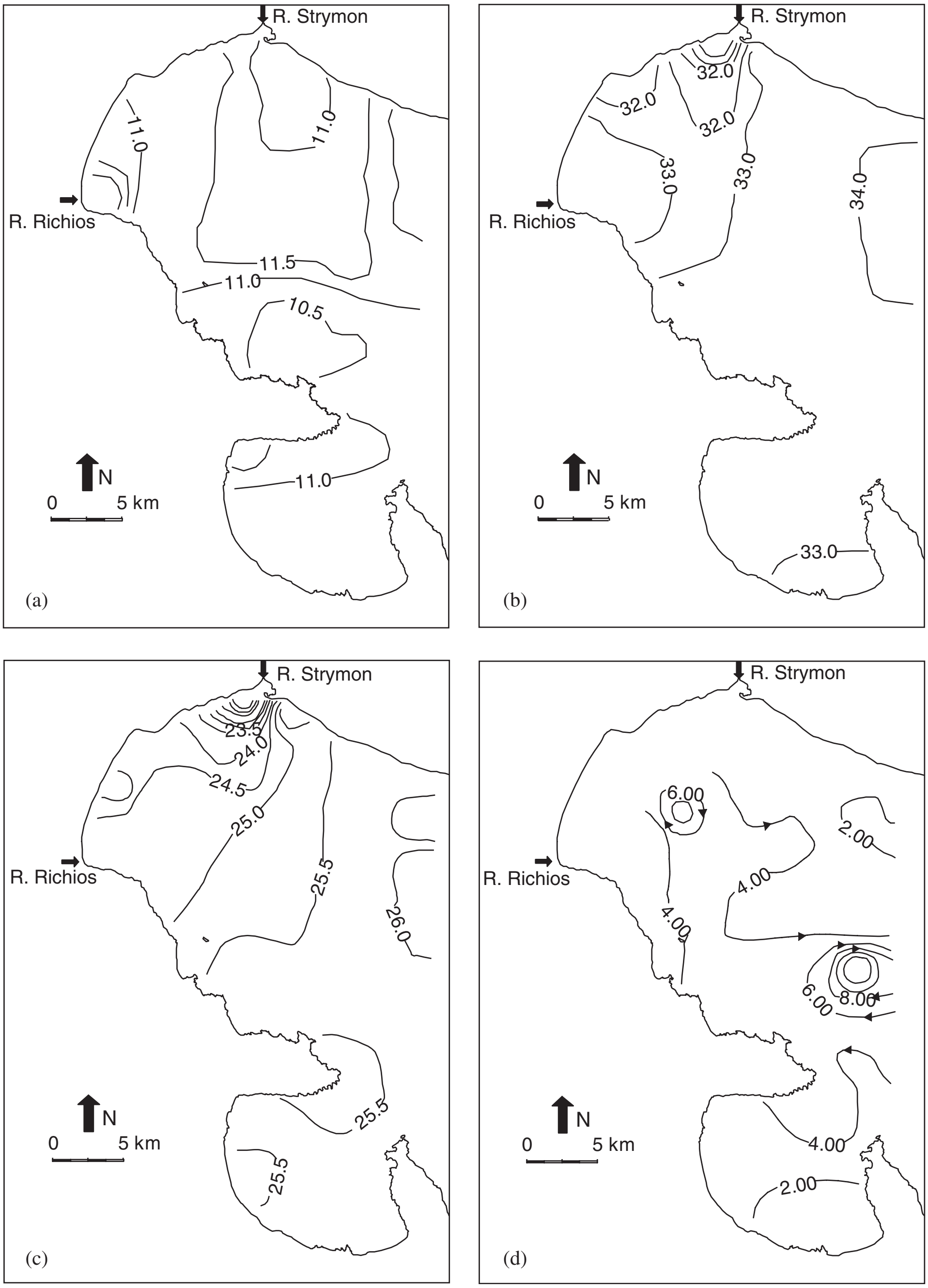

Fig. 8. Spatial distribution of (a) temperature (in °C), (b) salinity, (c) density σ_t and (d) dynamic height anomaly (in mm for 5/40 dbar), at the surface of Strymonikos and Ierissos Gulfs, during 20–22 February 1998.

observed in the winter period (1.14 μM in September to 17.92 μM in February).

The contribution of RPW and BSW in the overall nutrient content of the area was assessed using the above-mentioned reference salinity criterion to distinguish water masses. A distinct nutrient gradient from river mouth to the integrated river plume area and then to the remaining Strymonikos Gulf was observed in all seasons (Table 2). Figs. 11 and 12 present the mixing curves for DIN and DIP at the plume area and the remaining Strymonikos Gulf. During high river flow conditions (February), when

Fig. 9. Spatial distribution of (i) dissolved inorganic nitrogen (μM) and (ii) dissolved inorganic phosphorus (μM) during (a) June 1997, (b) September 1997, (c) November 1997 and (d) February 1998.

the gulf is rapidly flushed, nutrient concentrations appear linearly related to salinity indicating the conservative mixing behavior of the system. Such conservative mixing was mostly shown by the dissolved nitrogen and silicate distributions in the plume zone of Strymon River (DIN: $r^2 = 0.70$, $p<0.0001$; Si: $r^2 = 0.67$, $p<0.0001$). The absence of correlation during the summer and autumn periods seems associated with the low river flow conditions, inducing higher flushing rates, allowing the supplied material to be transformed, thus leading to a departure from conservative mixing.

4. Discussion

The North Aegean continental shelf, and especially the area surrounding Strymonikos Gulf, Athos peninsula, Thassos Island and Kavala Gulf, shows significant temporal variability patterns in physical parameters, as a result of the occurrence of less saline surface water of Black Sea origin (BSW), especially during the summer (Koukouras et al., 1984; Zervakis et al., 1998). Satellite imagery suggests that a branch of this low salinity surface water (varying from 33.0 psu during September to 37.5 psu during March) follows a cyclonic path along the northern coast of the Thracian Sea, causing a surface or subsurface salinity minimum near Mount Athos. This layer has a variable thickness (20–40 m in the Northern and NW Aegean), limited at its bottom by the 38.70 psu isohaline, depending on river discharges flowing into Black Sea and wind regime prevailing in North Aegean Sea (Yuce, 1995; Zodiatis et al., 1996). Recent observational studies (Koukouras et al., 1984) have recorded the presence of BSW at

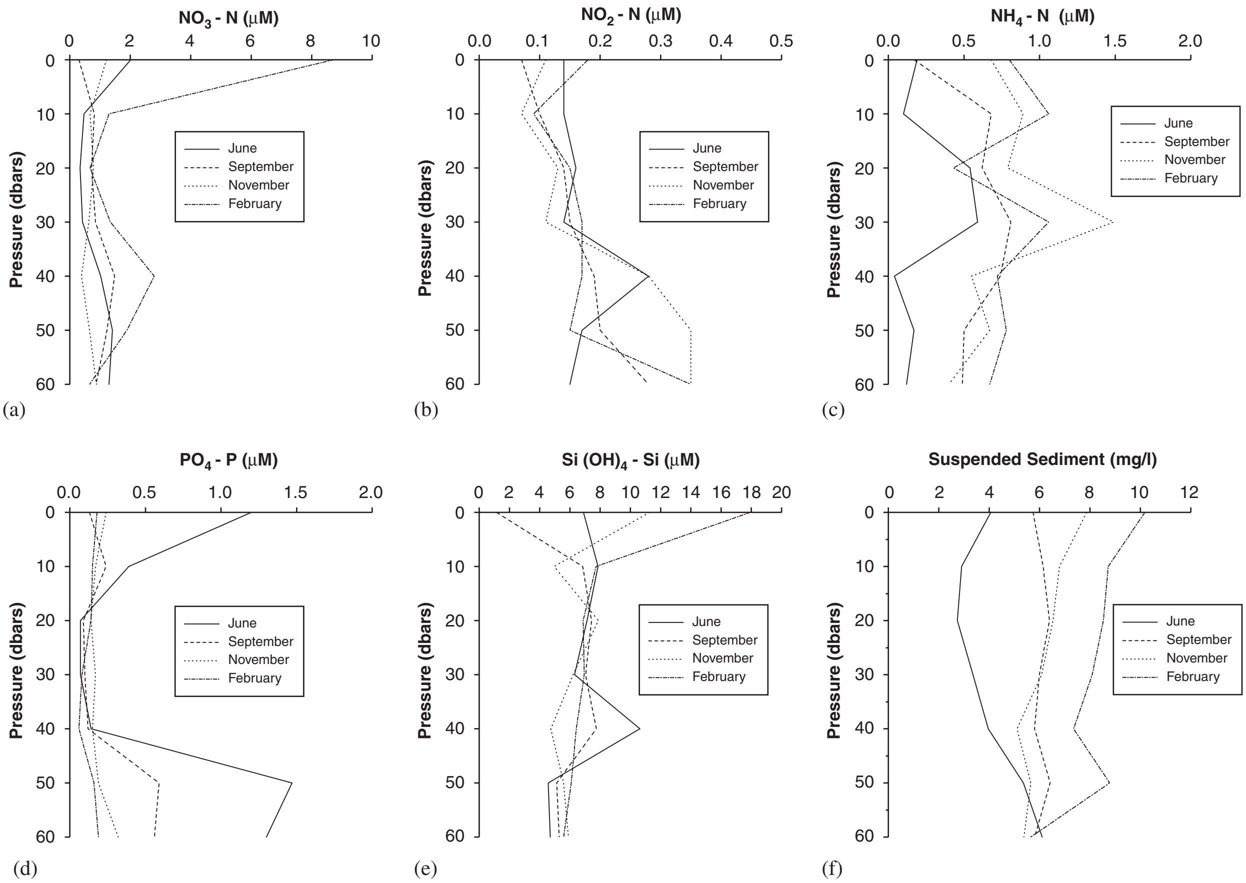

Fig. 10. Typical profiles of (a) nitrates, (b) nitrites, (c) ammonium, (d) phosphates, (e) silicates and (f) suspended sediments, during the four sampling periods at Strymonikos Gulf.

Strymonikos Gulf being mixed with the local freshwater of Rivers Strymon and Richios (Zervakis et al., 1998).

In this paper, $T-S$ analysis, as well as the horizontal distribution of hydrographic properties, revealed the relatively limited contribution of river inputs (PRW) from Rivers Strymon and Richios, especially during the summer and early autumn months. In June 1997, the lower limit of BSW ($S\sim38.7$) was recorded at the stations of the outer Strymonikos Gulf, thus allowing the intrusion of LIW ($T\sim14.5\,^{\circ}C$; $S\sim38.8$) into Strymonikos and Ierissos Gulfs. This pattern is probably caused by the decrease in BSW density and outflow from the Sea of Marmara to the North Aegean Sea, leading to a late summer maximum in water column stratification, which makes the surface water very thin and allows for the intrusion of LIW to shallower depths (Yuce, 1995). In autumn and winter, BSW obtains its maximum outflow from the Dardanelles (September) and deepens, thus occupying the whole water column of Strymonikos Gulf.

Surface water temperature in the nearshore zone appears controlled by local streams and torrents, showing an increase from shallow to deeper waters during the winter and a reverse pattern during the summer. Low water temperature occurs in the winter at the regions influenced from Rivers Strymon and Richios, due to the outflow of colder river water, especially under high river flow. Furthermore, sea surface temperature may be affected by the significant latent and sensible heat losses produced by the strong cold and dry northerly winds prevailing in the area during the winter. Salinity increases gradually with depth and distance from the coast, especially at areas unaffected from the direct buoyancy inflow of Rivers Strymon and Richios. Sea surface salinity varies seasonally according to river discharge and to BSW influence.

Table 2
Summary of nutrient concentrations during the four sampling periods

Chemical (μM)	June 1997	September 1997	November 1997	February 1998
Strymon River supply				
Nitrates	1.13	25.79	6.06	67.19
Nitrites	0.16	1.25	0.21	0.60
Ammonium	0.15	1.50	1.89	1.43
Phosphates	0.24	2.44	1.10	0.85
Silicates	2.30	76.64	63.31	77.19
Integrated River plume				
Nitrates	0.41	2.81	0.95	7.95
Nitrites	0.09	0.20	0.14	0.15
Ammonium	0.07	0.16	0.67	1.16
Phosphates	0.15	0.32	0.23	0.24
Silicates	1.09	10.37	8.80	15.69
Rest Strymonikos Gulf				
Nitrates	0.27	0.67	0.98	2.91
Nitrites	0.06	0.13	0.12	0.15
Ammonium	0.18	0.14	0.69	0.91
Phosphates	0.12	0.87	0.15	0.13
Silicates	1.20	6.27	8.40	9.81
Ierissos Gulf				
Nitrates	0.24	0.60	0.50	2.60
Nitrites	0.07	0.13	0.17	0.15
Ammonium	0.28	0.19	1.13	0.39
Phosphates	0.13	1.36	0.20	0.11
Silicates	1.09	4.85	4.04	8.75

Hence, the salinity cycle in Strymonikos Gulf shows two minimum values (~32.8–33.0), one in the winter (February 1998) when Kerkini Lake is not retaining freshwater and Strymon River discharge is maximum, and a second at the end of the summer (September), when BSW obtains low salinity values due to the annual maximum freshwater input of the Danube River (Yuce, 1995). This latter reduction of salinity values at the surface layer induces a higher stratification pattern in the water column and limits the thickness of BSW layer to maintain the same salinity anomaly content within a smaller water volume. Surface salinity obtains a peak value (34.5–35.0) during the summer when Strymon River input is almost negligible.

The spatial distribution of dissolved inorganic nutrients in Strymonikos Gulf was directly related to the amount of freshwater discharged by River Strymon. Nutrient concentration at the surface area in the mouth of Strymon River was always higher than those values recorded in the rest of Strymonikos Gulf. A distinct nutrient gradient exists between freshwater concentrations, the mixed plume zone and the rest of Strymonikos Gulf. Similar gradients of nutrient concentrations appear also near areas of local inputs such as Richios River mouth, Olympias and Ierissos coastline. Mean nitrates and ammonium concentrations presented important temporal variability ranging from 0.89 μM during the summer to 2.48 μM during the winter. This summer nitrogen depletion must be related to the phytoplankton growing season, in the shallow water of Strymonikos coastal zone and the euphotic zone of the offshore areas. Mean phosphates showed the reverse to nitrogen behavior with a high mean value of 0.66 μM during the summer period, decreased to 0.14 μM during the winter. The seasonal increases in DIP and decreases in DIN resulted in shifts in the mean gulf's DIN:DIP ratios, with values being very high (24.6:1) in the winter and low in the summer (2.1:1). Since DIN:DIP ratio is frequently applied as an indicator of the system's principal limiting nutrient, such occurrence indicates that Strymonikos Gulf changes from a phosphorus limitation system during the winter to a nitrogen limitation system during the late spring–early summer. The summer low ammonium values (5% of total DIN) at the river outflow suggest that upstream

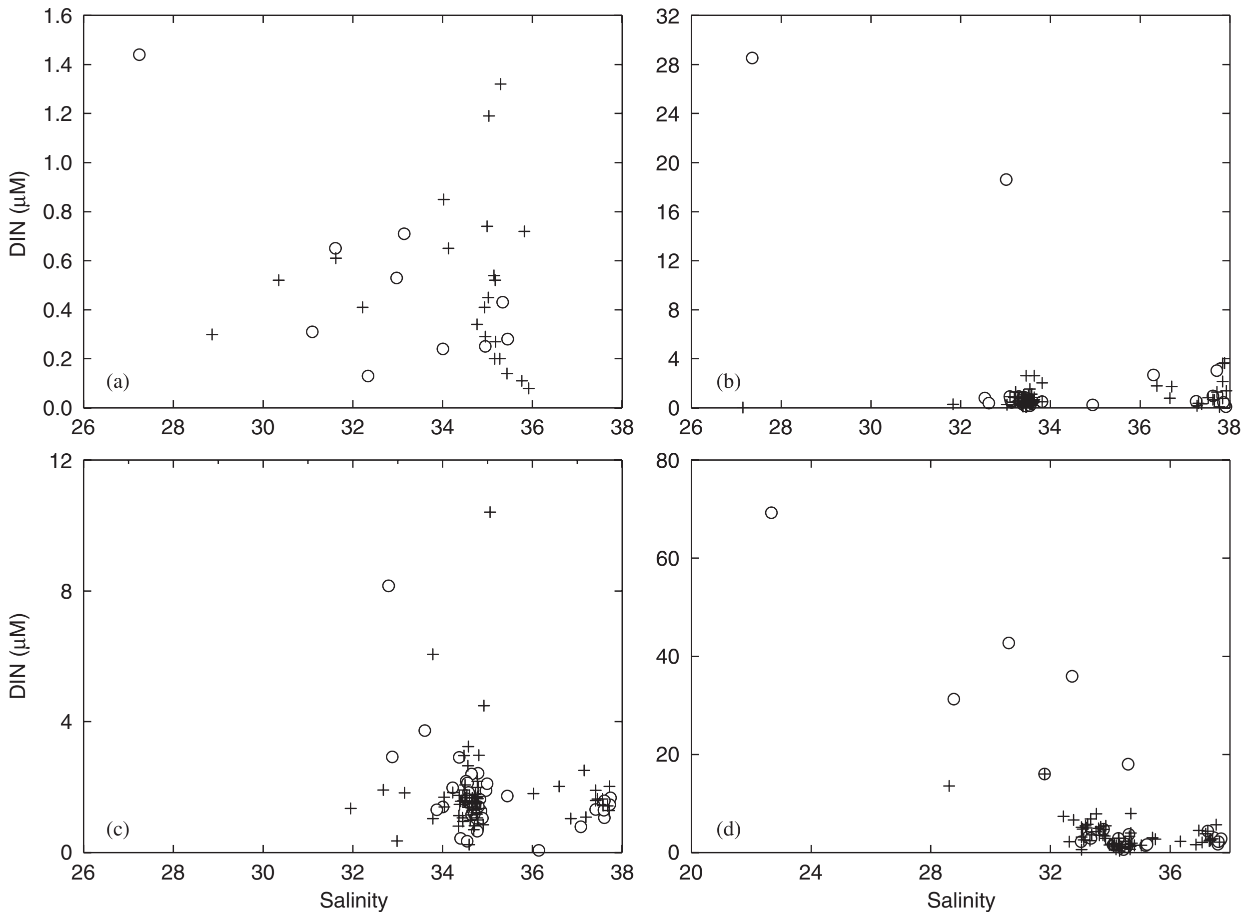

Fig. 11. Relations between dissolved inorganic nitrogen (DIN) concentrations and salinity in Strymonikos Gulf, during (a) June 1997, (b) September 1997, (c) November 1997 and (d) February 1998. Circles denote data within Strymon River plume and crosses in the remaining Strymonikos Gulf.

nitrification proceeded without transient accumulation of ammonium, and that nitrate was the nitrogen form of phytoplankton N-uptake within the Strymon River mixing zone. Pavlidou and Georgopoulos (2001) drew similar conclusions for this study area during their 1997–1999 samplings.

Analogous summer decreases in the DIN:DIP ratios have also been observed in other estuarine systems, e.g., the Hudson River (Lampman et al., 1999), the Danube River (Ragueneau et al., 2002) and the Chesapeake Bay (D'Elia, 1987). Although in most estuaries this behavior is mostly attributed to the seasonal changes in the nutrient cycling within the system, with the release of phosphorus from bottom sediments during late summer hypoxic events, this explanation is not valid for Strymonikos Gulf due to the mean high levels of dissolved oxygen prevailing at all layers of the water column throughout the year. We believe that the seasonal variability in the DIN:DIP ratio is largely due to the greater relative importance of untreated sewage and agricultural inputs during the low flow conditions of the summer period. This hypothesis is also supported by the similar seasonal pattern observed at the upstream of Strymon River, with DIN:DIP values ranging between 37:1 in the winter and 5:1 in the summer (Tryfon et al., 1996). In our data, the corresponding DIN:DIP ratios for the mouth of Strymon River range between 81:1 in the winter and 6:1 in the summer.

Since DSi:DIN ratios are of the order of 1:1 during summer, a summer surface nitrogen and silica depletion in Strymonikos and Ierissos Gulfs seems to take place, related to the rapid phytoplankton growth, the longer water renewal time and the limited vertical mixing to allow deep water

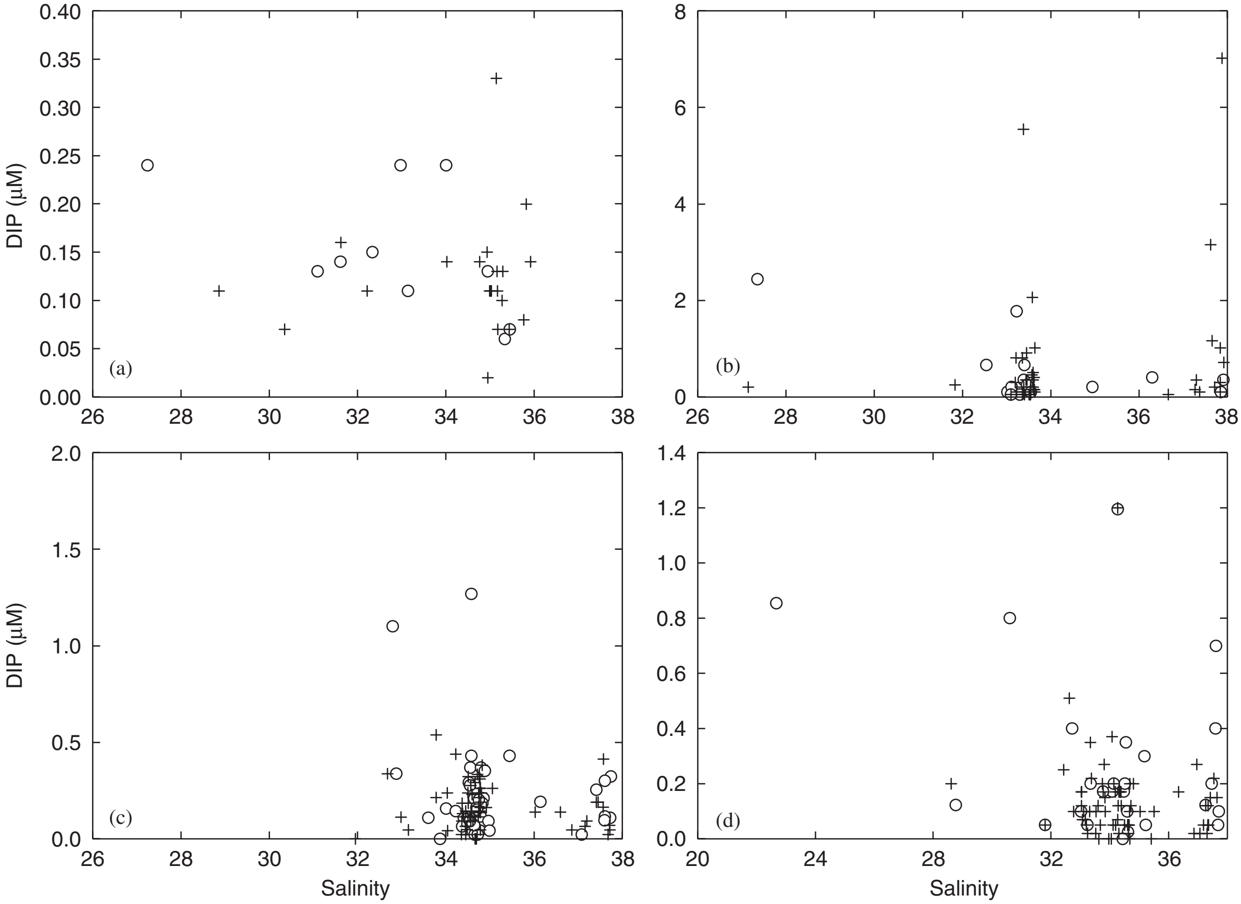

Fig. 12. Relations between dissolved inorganic phosphorus (DIP) concentrations and salinity in Strymonikos Gulf, during (a) June 1997, (b) September 1997, (c) November 1997 and (d) February 1998. Circles denote data within Strymon River plume and crosses in the remaining Strymonikos Gulf.

nutrients supply, due to the presence of the seasonal thermocline. In the winter, silicates increase in a similar manner to nitrates in the river plume zone, showing a DSi-excess at the marine end-member (DSi:DIN = 2.5). Active vertical mixing due to wind shear stress, effective water renewal from the combined strong river inputs and surface water runoff, together with limited phytoplankton growth resulting from low water temperature and solar radiation, inhibit winter nutrient depletion in estuarine environments (Salat et al., 2002).

The present study shows that the coastal circulation of Strymonikos Gulf is rich in mesoscale and smaller-scale features, including meanders, convergences, divergences and intrusion zones of low salinity surface water originated from Rivers Strymon and Richios. Geostrophic balance produced the 5/40 dbar topography, showing an inflow into Strymonikos Gulf at the northern part of its outer boundary section, and a sense of a counter-clockwise or cyclonic flow at the outer part of the gulf in June 1997. The cyclonic eddy at the boundary of Strymonikos Gulf seems relatively stable in the summer, since it has also been observed in May 1997 (Zervakis et al., 1998). On the contrary, during the rest of the sampling periods an anti-cyclonic flow prevails at the outer part of Strymonikos Gulf, directing the incoming water through the southern part of the boundary section. A well-established frontal zone separated the inner from the outer part of Strymonikos Gulf in June and September 1997. Water column stratification from solar heating and wind shear stress mixing govern the dynamics of the outer gulf, not directly affected by the RPW. Patterns at the inner gulf seem related to the freshwater discharge of

Rivers Strymon and Richios that enhance alongshore flow.

These river plumes appear as the dominant hydrographic features in the inner zone of Strymonikos Gulf. The river plume of Strymon gave the appearance of a point source with a horizontal extent of about 12 km rightward along the northwest coast of the gulf, affecting the area from river mouth to Asprovalta. Freshwater velocity at the mouth of Strymon River, estimated from transport considerations, was found ranging between $0.03\,\mathrm{m\,s^{-1}}$ during the summer low flow conditions and $0.4\,\mathrm{m\,s^{-1}}$ during the winter period. This indicates that the internal Froude number (F_I) near the mouth is continuously below 1 (0.15 in the summer to 0.8 in the winter), and therefore, the flow at the river mouth is subcritical. The spatial scale of river influence is defined by the inertial Rossby radius $L_I = u_f/f$, where u_f is the river inflow velocity and f the Coriolis acceleration. In Strymon River plume, this scale was found ranging between the order of 0.4–4 km during the low and high flow conditions, respectively.

Several other plume parameters help to characterize Strymon River plume in comparison to other regimes (Table 3). The baroclinic Rossby radius $L_B = (g'h)^{1/2}/f$, where g' is the density anomaly of the plume ($g' = \Delta\rho/\rho$) and h the thickness of the plume, ranges between 2.5 km for the summer and 5.1 km for the winter period. Thus, the mouth Kelvin number $K_m = L_m/L_B$ (where L_m is the plume width at the mouth) has an annual mean value of 1.6, indicating that inertial effects at the mouth are unimportant relative to Earth's rotation (Garvine, 1987). The maximum plume expansion W_S, assuming a buoyant discharge forming an anti-cyclonic thin layer moving over denser water, was derived following Yankovsky and Chapman (1997) as

$$W_S = L_B \frac{2(3+F_I^2)}{(2+F_I^2)^{1/2}}. \quad (3)$$

A mean W_S value of 15.5 km was produced ranging from 10 to 23 km according to river flow conditions. Calculated plume expansions correspond well to observations of plume width, defined by reference salinity values (Table 3). Sanchez-Arcilla and Simpson (2002) determined stratified shelf dynamics by comparing shelf width (L) to the maximum plume expansion (W_S). Strymonikos Gulf with approximate length of 30 km and an adjacent shelf width of 70 km is considered as a dynamically 'wide shelf' region in terms of stratification, thus freshwater layer flow appears decoupled from bottom topography at all seasons. In this case, circulation within the semi-enclosed water boundaries of the gulf will be the complex result of seasonally variant local driving agents (winds, density gradients due to river outflows) and ocean boundary forcings (along-shelf flow).

Considering the reference salinity value as the limit for direct freshwater influence, the horizontal area occupied by river water turns out to vary between 120 and 300 km^2. The relatively large plume surface coverage in summer (218 km^2), as compared to that observed in February (300 km^2), could be explained by the different stratification conditions, which prevented or delayed freshwater vertical mixing. Hence, while winter high river flow conditions favored vertical mixing inducing a thick homogeneous surface layer, the summer reduced river discharge produced a limited in depth plume that could easily spread across the area, maintaining its character and expanding due to limited mixing. The total freshwater content and its seasonal

Table 3
Seasonal variation of Strymon River plume parameters

	June 1997	September 1997	November 1997	February 1998
Strymon River discharge ($\mathrm{m^3\,s^{-1}}$)	12.5	3	43	147
Mouth freshwater layer depth (m)	1.5	1	2	4
Mouth freshwater velocity ($\mathrm{m\,s^{-1}}$)	0.1	0.03	0.2	0.4
Internal Froude number, F_I	0.29	0.15	0.65	0.8
Inertial Rossby radius, L_I (km)	0.9	0.4	2.4	4
Baroclinic Rossby radius, L_B (km)	3.1	2.5	3.7	5.1
Mouth Kelvin number, K_m	1.11	2.30	1.78	1.35
Maximum plume expansion, W_S (km)	13.5	10	16	23
Observed plume expansion (km)	12.3	9.7	11.5	18.8

variability in Strymonikos Gulf were estimated by integrating local freshwater fractions over the estuary's volume. It was found to vary from 12.6×10^6 to $65.8\times10^6\,m^3$ during the summer and winter periods, respectively. A similar analysis was also conducted by Hyder et al. (2002) to compute the freshwater content in Thermaikos Gulf, which was found to change seasonally from 350×10^6 to $800\times10^6\,m^3$. Dividing freshwater volume to the freshwater surface coverage produces an equivalent freshwater surface elevation of 0.09–0.21 m. The above freshwater balance was then used to calculate the residence time of water within the gulf. This analysis provides an average time scale for the conservative transport of river-borne materials, such as nutrients, organic matter and pollutants, through the estuary. For each sampling cruise, a mean Strymon River discharge was then considered by averaging over the period of the residence time itself (Alber and Sheldon, 1999). It occurred that freshwater residence time varies between 5 and 48 days, under high and low Strymon River flow conditions, respectively. However, since wind influence is considered a principal forcing in the area, with the winter strong northerly 'Vardaris' winds and the summer northerly southerly directed sea breeze winds prevailing in the area, the estimated freshwater exchange is expected to change. Therefore, landward Ekman transports induced in the surface layer during the south and southeastern winds, are expected to confine river plume to the inner shelf, causing a sea surface setup accompanied by the deepening of the pycnocline. Conversely, the abrupt change in wind to a northerly direction tends to spread the plume across the shelf, thus weakening the cross-plume baroclinic gradient, as the plume advects offshore, but resulting to a wind-enhanced estuarine exchange.

Although estuarine dynamics were crudely estimated by the freshwater residence time, its seasonal variation illustrates the impact of man-controlled freshwater discharge alterations (e.g., for irrigation purposes) on the function of coastal semi-enclosed ecosystems. Moreover, since a series of key ecosystem processes as denitrification, nutrient retention and recycling, phytoplankton bloom development and net ecosystem metabolism are controlled by freshwater flushing time, river flow seasonal extremes influence directly the estuarine nutrient mixing mechanism and its nutrient retention efficiency (Eyre, 1998). In general, Kerkini Lake water retention has a direct impact on Strymonikos Gulf estuarine circulation patterns, salinity gradients, sediment transport and nutrient supplies, affecting also the level of stratification which largely determines vertical mixing, and hence the vertical fluxes of water properties, such as heat, salt, momentum and nutrients. Kerkini Lake operators should allow a summer Strymon River flow of at least $30–40\,m^3\,s^{-1}$, to limit upstream seawater intrusion and release gradually in the autumn the summer retained water, thus preserving natural variability in estuarine hydrodynamics and biogeochemistry.

5. Conclusions

In this paper, the results of four field campaigns carried out during June, September, November 1997 and February 1998 were used to examine the differences in hydrographic and nutrient behavior in Strymonikos and Ierissos Gulfs, two semi-enclosed coastal water bodies in Northern Greece. These new observations indicated the distinct winter and summer regimes, influencing the water mass and nutrient distributions in the area of interest. Hydrographic patterns and nutrient distributions in the area appear mostly enhanced by the Kerkini Dam-controlled river flow rates. Inner Strymonikos Gulf is characterized by a river flow-dependent two-layer system, while outer Strymonikos and Ierissos Gulfs by well-mixed conditions. Several interesting dynamic processes were emphasized in the region of freshwater influence, at the vicinity of Strymon and Richios River mouths. Mesoscale and smaller-scale features were revealed due to the horizontal density variability associated with Strymon and Richios River discharges. River discharge and BSW influences strongly the temporal salinity cycle of Strymonikos and Ierissos Gulfs. Two minimum values were recorded, one in the winter under high river flow conditions (Kerkini Dam not operating), and a second during autumn due to BSW influence. During the summer, BSW becomes shallower (up to 55 m) and LIW enters the deeper parts of the outer Strymonikos Gulf.

Nutrients (DIN, DIP and Si) were supplied in Strymonikos Gulf by Strymon and Richios freshwater discharge, producing a distinct nutrient gradient between freshwater inflow, the mixed plume zone and the remaining system. Under low to moderate river discharge conditions, nutrient concentrations appeared highly scattered and not linearly related to salinity, due to higher flushing rates allowing nutrients transformation. In the winter, rapid flushing in Strymon River plume area induces the conservative mixing of dissolved nitrogen and silicate. DIN and DIP concentrations followed opposite temporal variability patterns, with low DIN values in the summer and high in the winter. The computed DIN:DIP ratios illustrated the system's seasonal variability, shifting from a winter P-limitation to a summer N-limitation behavior. Nitrate was the nitrogen form contributed to phytoplankton uptake within the Strymon River mixing zone. DSi follows the DIN temporal variation, showing a winter DSi-excess seaward in the Strymon River plume zone, associated with the effective water flushing and the limited phytoplankton growth during that period.

Strymon and Richios River plumes appeared as the dominant hydrographic features in the near-shore zone of Strymonikos Gulf. Freshwater input extended horizontally with a rightward deflection along the northwestern coast of the gulf, with a plume width ranging from summer to winter between 10 and 23 km, and a plume thickness varying from 1 to 4 m, respectively. Maximum plume expansion indicated that this is a dynamically 'wide shelf' region, affected by the seasonally variable local forcing and the along-shelf circulation. The total freshwater content in Strymonikos Gulf was calculated to vary from 12.6×10^6 to $65.8 \times 10^6\,m^3$ during the summer and winter periods, respectively. This variability leads to a freshwater residence time ranging between 5 and 48 days, according to Strymon river flow conditions.

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