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Residual currents and fluxes through the mouth of Vassova coastal lagoon

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Abstract

An intensive sampling program of physical and chemical parameters at the mouth of Vassova lagoon (Northern Greece) during 4 separate tidal cycles is described. The study aims at understanding the tidal circulation and estimating the instantaneous and residual fluxes of water, salt and nutrients through the entrance canal of this micro-tidal lagoon. Results showed that tidal flood exceeded in duration tidal ebb, under spring and neap tidal conditions. Ebb tidal currents were recorded higher than flood currents, especially under neap tidal conditions. Unsteady flow characterized the temporal variation of longitudinal and lateral velocity, inducing a rightward deflection on flood or ebb flow. The intra-tidal variability of dissolved inorganic nitrogen showed seasonal dependence, with higher values during September, October and early March, and lower during the late March period. Residual current and flux analysis into a Eulerian and a mass transport Stokes drift mechanism illustrated that advective water and dissolved parameters (i.e., salt and nitrates, phosphates and chlorophyll-α) fluxes were an order of magnitude higher than tidal pumping effects. Water and dissolved constituents moved into the lagoon under neap tidal conditions and out of the lagoon during spring tidal conditions. Calculated flushing times ranged from 5 to 14 days, with neap tidal conditions and nearly zero freshwater discharge producing the longer flushing time. Lower water flushing effects were generated under spring tides and increased precipitation.

Keywords: Coastal lagoon, Vassova, Residual currents, Salt flux, Untrient fluxes.

Introduction

Mediterranean coastal lagoons are small in size and shallow water bodies, formed by a mixture of brackish and sea water. These geomorphic features have a main basin with a parallel to the coast orientation, being separated partially from the adjacent sea by sand bars, which are formed at their mouths (BARNES, 1980). Mediterranean coastal lagoons have been classified according to a series of common geomorphologic and ecological features by PHLEGER (1981) and NIXON (1982). Sufficient sediment supply from the adjacent river mouth and strong littoral currents in the coastal zone may result in the development of a single, long, narrow entrance channel, classifying the lagoon in the group of chocked lagoons (KJERFVE, 1986; KJERFVE & MAGILL, 1989). The water circulation within a coastal Mediterranean micro-tidal lagoon is mostly characterized by low tidal oscillations, on which residual water circulations are superimposed. These may be generated by the non-linear interactions between tidal flow and lagoon topography, density gradients, wind stress and the mass input due to freshwater discharges into the system (AL-RAMADHAN, 1988).

Instantaneous and residual currents and fluxes through the lagoon mouth boundary can produce drastic changes in the balance of ecological processes and alter the fluctuations of the physical and chemical characteristics that are the basis of high productivity in a coastal lagoon (COMIN, 1982; SIMPSON *et al.*, 2001). Water fluxes control the flushing of the coastal lagoon, thereby maintaining water quality, and provide a mechanism for planktonic inward/outward transport (GORDO & CABRAL, 2001). Salt fluxes determine the estuarine characteristics of the lagoon and define floral and faunal community structure and the spatial distribution of fish. Dissolved inorganic nutrients and chlorophyll-α are the raw materials directly affecting the marine trophic chain. Coastal lagoons serve as buffer zones for nutrient storage and fluxes coming from adjacent continental drainage to the marine environment (PEREIRA-FILHO *et al.*, 2001).

A series of nine chocked, shallow and elongated coastal lagoons have been formed at the western bank of the Nestos River delta (Northern Greece), covering a total wetland area of 17 km^2. Vassova (40° 57′N, 24°34′E) is a small (area: 0.7 km^2), shallow (mean depth: 0.7 m), coastal lagoon. The lagoon is exploited for fish production (30,000 kg/year; KOKKINAKIS *et al.*, 1997), therefore its topographic configuration is formed to consist of a central main basin and 13 dredged wintering canals, ranging from 30 to 50 m long and 0.5 m deep each (Fig. 1). SYLAIOS & THEOCHARIS (2002) computed the lagoon annual water balance and predicted a mean annual value of freshwater runoff discharge through seepage of 0.940 $m^3\ s^{-1}$. Evaporation (mean annual value: 990 mm) exceeds precipitation (mean annual value: 490 mm), resulting in a mean annual evaporative outfluxe of 0.085 $m^3\ s^{-1}$ and a mean annual precipitation influx of 0.042 $m^3\ s^{-1}$ (SYLAIOS & THEOCHARIS, 2002). The lagoon communicates freely through its entrance canal with the open sea (Kavala Gulf) and is forced by a semi-diurnal micro-tidal wave with a spring range of approximately 0.40 m and a neap range of 0.15 m.

Nestos river lagoons act as buffer zones for the transfer of agricultural nutrients from the Chrisoupolis plain to the Kavala Gulf's coastal zone (THEOCHARIS *et al.*, 2000; SYLAIOS & THEOCHARIS, 2002). On the other hand, the eastern part of the Kavala Gulf receives significant amounts of dissolved inorganic nitrogen and phosphorus, mainly from the operations of a nearby phosphoric fertilizer factory and the two wastewater treatment plants of the city of Kavala, as well as from four drainage canals of the Chrisoupolis plain, which outflow nutrient-rich agricultural runoff and irrigation water directly to Kavala Gulf, especially during the winter (SYLAIOS *et al.*, 2002). Thus, the exchange dynamics at the Vassova lagoon mouth serve as a basis for understanding the mechanisms responsible for water, salt and nutrient transport on an intra-tidal time scale. In order to evaluate the current lagoon ecological condition and functions, a study was undertaken comprising of: (a) an intensive monitoring program of hydrographic and water quality parameters at the lagoon mouth, during various tidal cycles and meteorological conditions; (b) quantification of the instantaneous and residual fluxes of water, salt and nutrients across the lagoon mouth, in order to obtain a synoptic flux data set, which could be used to generalize

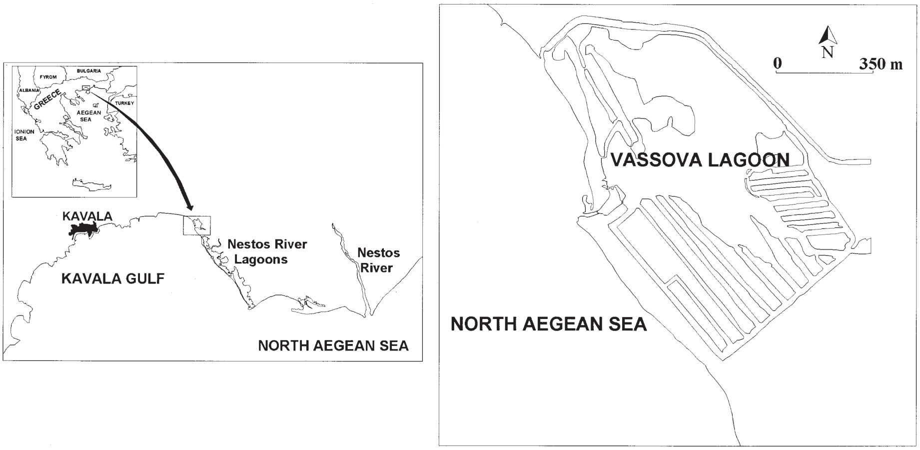

Fig. 1: Map of Vassova lagoon in Northeast Greece.

conclusions; (c) computations of pollutant loadings from and to the open sea, thus identifying sources of pollution; and (d) based on the above, proposing methods for improving fish production, while improving ambient conditions in the lagoon and maintaining ecological integrity.

Materials and Methods

Sampling Strategy and Specific Site Description

The principal data set to be considered consist of four 12.5 hr continuous time series of velocity, surface elevation, salinity, temperature, dissolved oxygen and dissolved inorganic nutrients (nitrates and orthophosphates), obtained from an instrument deployment at two positions along the Vassova lagoon entrance canal. Hydrographic and water quality data were obtained under different tidal, wind magnitude and direction, and fresh water inflow conditions, thus allowing the direct relation of transport mechanisms with the above described external factors.

The entrance canal of Vassova lagoon has a total length of 78 m, and is divided into three parts as one moves from the sea into the lagoon: (a) a 18 m-long and 11 m-wide canal with an E-W direction; (b) a 22 m-long and 13.5 m-wide canal with a NE-SW direction (77°); and (c) a 38 m-long and 11 m-wide canal with an ENE-WSW direction (66°) (Fig. 2). In the middle of this third part of the canal there exists a bridge (outer bridge) from which measurements of flow and water quality characteristics were made. After the entrance canal there follows a basin separated into two parts: the first part is 66 m long, 41 m wide and is directed SSW-NNE (47°), and the second part is 45 m long, 33 m wide in a S-N direction. Two entrances, one at the north and the other at the northeast connect this basin with the main body of the lagoon. At the northern entrance the fishery facilities (entrapment devices) of the Vassova lagoon are located, similar to those described by PAULY & YANEZ-ARANCIBIA (1994). At the northeastern entrance is a bridge, where the water flow is either totally open or controlled either by grilled barriers (partially blocked, 8 mm width between vertical bars) or by wooden barriers (fully blocked) which work as weirs. This bridge is the second site (inner bridge) where instantaneous measurements of water flow and quality parameters were taken (Fig. 2).

Data Collection

The principal data set to be considered consist of four complete tidal cycles (27

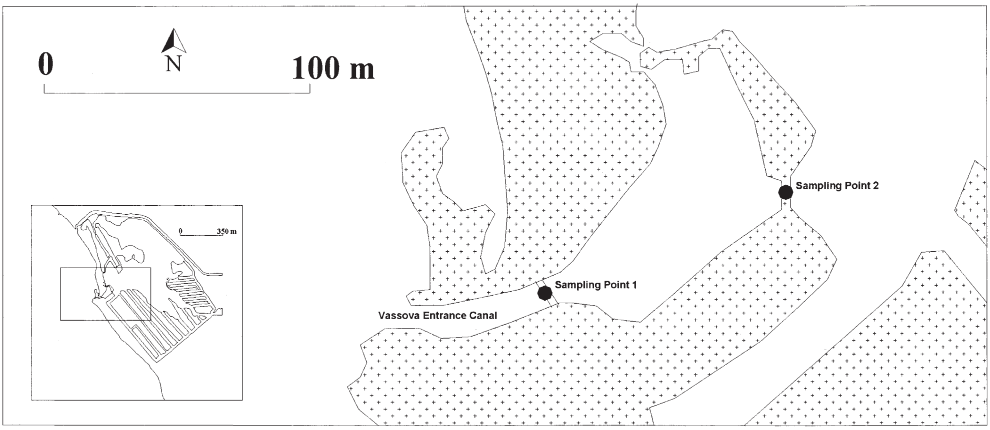

Fig. 2: Map of Vassova lagoon showing the entrance canal and the location of sampling sites.

September 2001; 3 October 2001; 7 March 2002; and 21 March 2002) obtained under various tidal and meteorological conditions (Table 1) at two positions along the mouth of Vassova lagoon (outer and inner bridge). A number of hydrographic (velocity and tidal elevation) and water quality parameters (temperature, salinity, dissolved oxygen concentration) were monitored with a 3-min time-step, using a range of self-recording instrumentation, which is presented in Table 2. Furthermore, direct reading instrumentation was also deployed from both bridges, for comparative purposes, using a 3 to 15-min recording time-step (Table 3).

Meteorological data (air temperature, atmospheric pressure, air humidity, wind velocity and direction and precipitation) were also recorded on site using an ELE MM900/950 meteorological station, during the 12.5 hr sampling period. Evaporation was measured using a standard US class A pan. Furthermore, records of these meteorological parameters were also obtained for comparison from the National Meteorological Service Station (Chrisoupolis Airport) for the week prior to and during the sampling day.

Salinity was determined using temperature and electrical conductivity values based on the equation of state and UNESCO tables (UNESCO, 1981). Finally, water samples were collected at both sampling points every hour, filtered immediately after they were taken through Whatman GF/C 0.45 μm filters, frozen and stored in separate 50 ml polyethylene bottles, for analytic nutrient determination. Nitrates were analyzed using the methods described by GRASSHOFF (1983) and o-phosphates according to PARSONS *et al.* (1984). Dissolved nutrients were derivatized with reagents pro analysi (Merck, Riedel de Haen) made fresh daily with deionized water and concentrations were calculated from standard curves produced on a spectrophotometer. The chlorophyll-α was extracted using 90% acetone. Extracts were left refrigerated for 24 hrs, centrifuged and the supernatant was measured on a double beam spectrophotometer at 630, 647 and 664 nm, according to PARSONS *et al.* 1984.

Instantaneous and Residual Flux Estimation

The system for describing current measurements was defined by having the positive longitudinal axis directed towards the lagoon (northwest direction) and the positive lateral axis to its right (southeast direction). Following UNCLES & JORDAN (1979) and UNCLES *et al.* (1986), the instantaneous rate of water transport per unit of width through a water column of depth H is given by Q ($m^3\ s^{-1}\ m^{-1}$) as:

$$Q = H\bar{U} = H\,(\bar{u},\bar{v}) \qquad (1)$$

where u,v are components of the longitudinal U-velocity ($m\ s^{-1}$) in the x, y directions, respectively. The overbar denotes an average over depth.

The residual rate of water transport is given by:

$$\langle Q \rangle = \langle H \rangle \cdot \left[V_1 + V_2 \right] \qquad (2)$$

where $\langle n \rangle$ represents the tidal average of a variable, V_1 ($m\ s^{-1}$) the depth-averaged Eulerian residual transport, or the non-tidal drift, which is expressed by DYER (1974) as:

$$V_1 = \langle \bar{U} \rangle \qquad (3)$$

and V_2 ($m\ s^{-1}$) a measure of the residual rate of water transport resulting from tidal

Table 1
Tidal and meteorological conditions prevailing during sampled tidal cycles at Vassova lagoon.

Date	Tidal Range (m)	Tidal Status	Average Depth (m)	Rainfall (mm)	Mean Wind Speed (m/s)	Wind Direction	Evaporation ($mm\ h^{-1}$)
27-9-2001	0.23	Intermediate	0.97	31.2	0.8	S	n/a
3-10-2001	0.29	Spring	0.89	0.3	0.3	NE	0.27
7-3-2002	0.07	Neap	0.77	0.0	0.5	SW	0.19
21-3-2002	0.19	Intermediate	0.81	0.0	1.1	NE	n/a

n/a = no data available

Table 2
Self-recording instrumentation used for monitoring intratidal variability.

Instrumentation	Parameters measured	Range	Accuracy
Valeport 105	Velocity and direction	0 – 5 m/s	0.01 m/s; ± 0.6°
Valeport VLR 740	Tidal elevation	0 – 10 m	± 0.01%
CTD Idronaut 301	Temperature	(-1) – (+50)°C	± 0.02%
	Conductivity	0 – 62 mS/cm	± 0.03%
YSI 6820 Multi – Parameter Probe	Conductivity	0 – 100 mS/cm	± 0.5%
	Dissolved Oxygen	0 – 50 mg/l	± 2%
	pH	0 – 14	± 0.2%
	Nitrate (NO_3)	0 – 200 mg/l	± 10%
	Ammonium (NH_4)	0 – 200 mg/l	± 10%
	Ammonia (NH_3)	0 – 200 mg/l	± 10%
	Total Dissolved Solids		
	Turbidity		

Table 3
Direct reading instrumentation used in the sampling program.

Instrumentation	Parameters measured	Range	Accuracy
Valeport 801 Electromagnetic current-meter	Velocity	0 – 5 $m\ s^{-1}$	0.01 m/s
WTW 197	Conductivity	10^{-2}x10^6 $\mu S\ cm^{-1}$	± 1%
	Dissolved oxygen	0 – 50 $mg\ l^{-1}$	
	pH	0 – 14	

pumping, which is expressed by HUNTER (1972) and TEE (1976) as:

$$V_2 = <\tilde{H}\tilde{U}> / <H> \tag{4}$$

where $\tilde{H}$, $\tilde{U}$, represent the depth-averaged instantaneous deviations of water depth and velocity from the tidal mean. The V_2 current is referred to as the mass transport Stokes drift, to distinguish it from the related Stokes drift.

Similarly, the instantaneous transport rate of salt, Qs (10^{-3} kg s^{-1} m^{-1}), per unit of width through a column of depth H, is given by:

$$Q_S = H\overline{US} \tag{5}$$

The residual transport rate of salt is in the form:

$$\langle Q_S \rangle = \langle H \rangle \left[V_{S,1} + V_{S,2} + V_{S,3} \right] \tag{6}$$

where $V_{S,1}$ (10^{-3} kg s^{-1} m^{-2}) represents the depth-averaged residual flux of salt due to the residual transport of water, and is expressed as:

$$V_{S,1} = \langle Q \rangle \langle \bar{S} \rangle / \langle H \rangle \tag{7}$$

where $V_{S,2}$ (10^{-3} kg s^{-1} m^{-2}) represents the depth-averaged residual flux due to tidal pumping, resulting from the non-zero correlations between Q and S, expressed as:

$$V_{S,2} = \langle \tilde{Q}\tilde{S} \rangle / \langle H \rangle \tag{8}$$

and $V_{S,3}$ (10^{-3} kg s^{-1} m^{-2}) represents the depth-averaged residual flux of salt due to the vertical shear between the tidal and residual currents, expressed as:

$$V_{S,3} = \langle H\, \overline{V'S'} \rangle \langle H \rangle \tag{9}$$

where V′ and S′ represent the deviations of velocity and the concentration of salt from the depth-averaged value, respectively. In Vassova lagoon, where the column of water is well-mixed, the term $V_{S,3}$ was negligible, because $S' \sim 0$. Finally, the instantaneous and residual transport rates of any water constituent (e.g., nutrients, suspended sediments, chlorophyll-α), was computed following the above Eqs. (5) to (9) by substituting salinity with the appropriate water constituent concentrations (UNCLES *et al.*, 1986).

Tidal Prism Estimation

The instantaneous local water fluxes per unit of width Q (m^3 s^{-1} m^{-1}) can be integrated over the flood and ebb period, respectively, resulting in:

$$V_{Flood}(y) = \int_{t=0}^{t=\tau} Q \, dt \tag{10}$$

and

$$V_{Ebb}(y) = \int_{t=\tau}^{t=T} Q \, dt \tag{11}$$

in which $V_{Flood}(y)$ or $V_{Ebb}(y)$ (m^3 m^{-1}) represent the tidal prism during flood or ebb period per meter of width (m^3 m^{-1}), T is the tidal period (approximately 45,000 s) and t=0, t=τ and t=T represent the slack tidal times. The tidal prism per unit of width (m^3 m^{-1}) is, therefore, defined as $V_{Prism} = V_{Flood} - V_{Ebb}$ (DE JONGE, 1992).

Results and Discussion

Instantaneous Fields

The characteristics of the observed currents and salinity regime are summarized for each tidal period in Table 4. In general, tidal range at Vassova lagoon varied from 0.07 m to 0.29 m during neap and spring tidal conditions respectively, with tidal elevation following mostly the semi-diurnal M_2 motion. Flood duration ranged from 2.6 to 9.3 hrs, being mostly higher than corresponding ebb duration (3.25 to 9.9 hrs), apart from the September 2001 tidal cycle, when the reverse effect occurred. However, ebb mean and maximum currents were stronger than the corresponding flood currents, with a typical inward flow of

Table 4
Summary characteristics of each tidal cycle sampled at Vassova lagoon.

Tidal parameter	**27-9-2001**	**3-10-2001**	**7-3-2002**	**21-3-2002**
Tidal Range (m)	0.23	0.29	0.07	0.19
Tidal Status	Intermediate Tide	Spring Tide	Neap Tide	Intermediate Tide
Ebb Duration (min)	594	396	195	294
Time to Max. Ebb (min)	306	234	51	141
Max. Ebb (m s^{-1})	0.89	0.77	0.33	0.73
Mean Ebb (m s^{-1})	0.36	0.52	0.13	0.24
Flood Duration (min)	156	354	555	456
Time to Max. Flood (min)	42	180	42	327
Max. Flood (m s^{-1})	0.58	0.60	0.38	0.66
Mean Flood (m s^{-1})	0.23	0.38	0.16	0.16
Tidal Range (m s^{-1})	1.47	1.37	0.71	1.39
Tidal Mean (m s^{-1})	-0.25	-0.10	0.08	-0.01
Ratio 1	0.79	0.53	0.26	0.39
Ratio 2	0.51	0.59	0.26	0.48
Ratio 3	0.21	0.47	0.74	0.61
Ratio 4	0.27	0.51	0.07	0.72
Ratio 5	1.53	1.28	0.86	1.10

Ratio 1 = ebb duration / total duration of tidal cycle; Ratio 2 = time to maximum ebb / total ebb duration; Ratio 3 = flood duration / total duration of tidal cycle; Ratio 4 = time to maximum flood / total flood duration; Ratio 5 = maximum ebb current / maximum flood current.

0.38 m s^{-1} during spring tide and 0.16 m s^{-1} during neap tide, and an outflow speed of 0.52 m s^{-1} and 0.13 m s^{-1}, respectively. The average ratio of the maximum ebb to maximum flood current (Ratio 5; Table 4) ranged from 0.86 during the 7-3-2002 neap tidal cycle to 1.53 during the 27-9-2001 intermediate tide.

Following the tidal characteristics of a representative spring tidal cycle (3-10-2001) it occurs that tidal ebb has a duration of 396 min (6 hrs 36 min or 53% of the tidal cycle), a maximum longitudinal ebb current of 0.77 m s^{-1} and a mean longitudinal ebb current of 0.52 m s^{-1}. Tidal flood duration is 354 min (5 hrs 54 min or 47% of the tidal cycle) with a maximum longitudinal flood current of 0.60 m s^{-1} and a mean flood current of 0.38 m s^{-1}. Maximum ebb and flood flow occurred just past midway in the ebb (Ratio 2 = 0.59) and flood phase (Ratio 4 = 0.51), respectively (Table 4).

Under neap tidal conditions (7-3-2002) tidal ebb lasts for 195 min (3 hrs 15 min or 26% of the tidal cycle), producing a maximum longitudinal ebb current of 0.33 m s^{-1} and a mean longitudinal ebb current of 0.13 m s^{-1}. Tidal flood duration is 555 min (9 hrs 15 min or 74% of the tidal cycle) with a maximum longitudinal flood current of 0.38 m s^{-1} and a mean flood current of 0.16 m s^{-1}. Maximum ebb currents occurred very early in the ebb phase (51 min into the ebb phase; Ratio 2 = 0.26), and maximum flood flow occurred 42 min into the flood phase (Ratio 4 = 0.07).

Figure 3 presents the temporal variability of longitudinal and lateral velocity at the mouth of Vassova lagoon, during the four different tidal cycles. Longitudinal velocity has a semidiurnal behavior during 2-10-2001 spring tide, but continuous reversals in the flow field during all other three tidal periods. Therefore, flood and ebb phases do not appear well defined in the longitudinal flow field under neap and intermediate tidal conditions.

Lateral velocity shows intervals of unsteady behavior, similar to the longitudinal velocity component. In general, inward transport is associated with positive lateral velocity sign, deflecting water towards the southeastern part

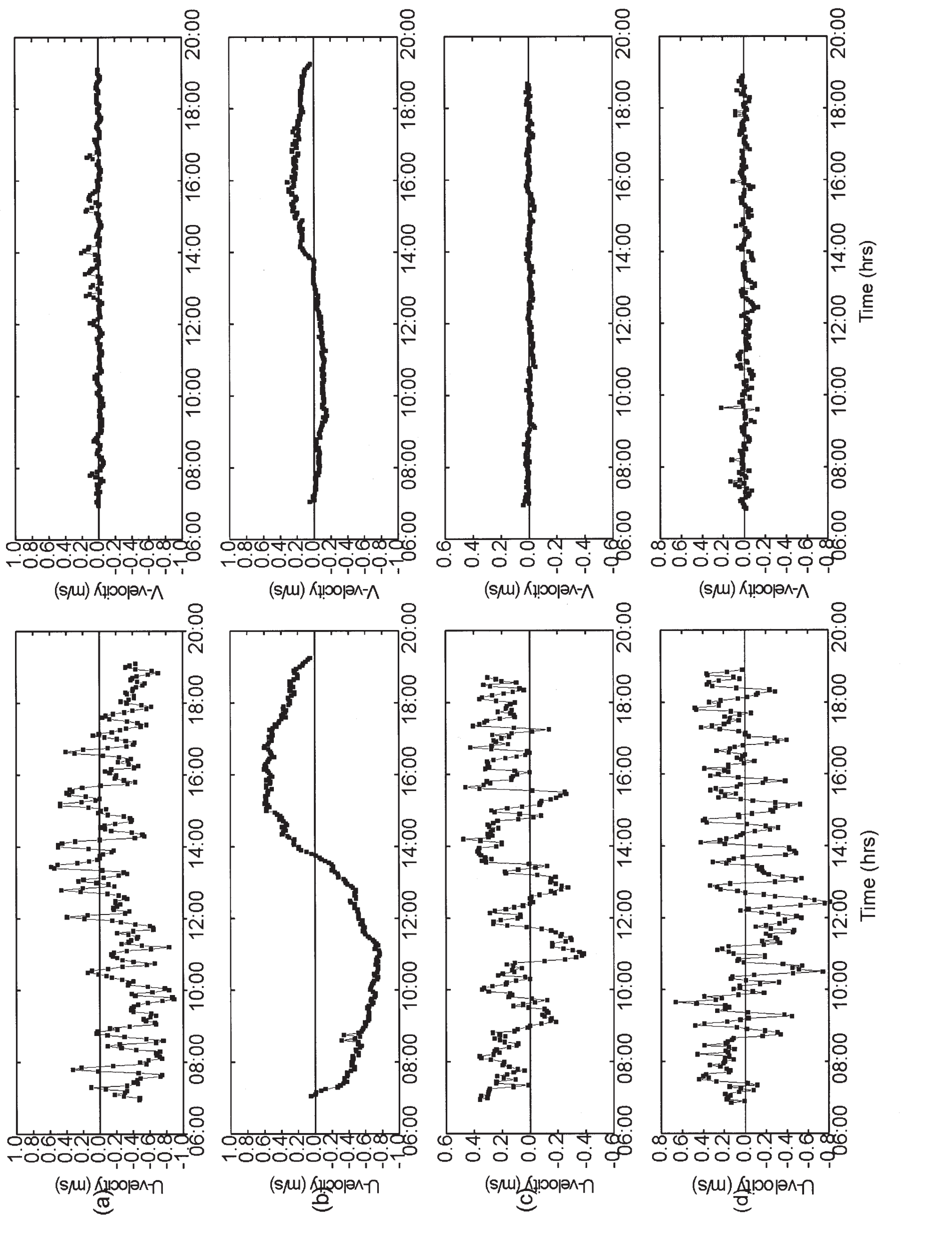

Fig. 3: Longitudinal (U-velocity) and lateral (V-velocity) intra-tidal variability at Vassova entrance canal, during (a) 27-9-2001; (b) 3-10-2001; (c) 7-3-2002, and (d) 21-3-2002.

of the entrance canal. However, the weak longitudinal flow pattern recorded during the 27-9-2001, 7-3-2001 and 21-3-2001 neap and intermediate tides enhances lateral deviations towards both parts of the channel with rapid change.

The temporal variability of tidal elevation and salinity during each tidal cycle sampled at the Vassova lagoon mouth is illustrated in Fig. 4. Random salinity profiles obtained during different tidal stages showed vertical homogeneity of the water column. Strong tidal

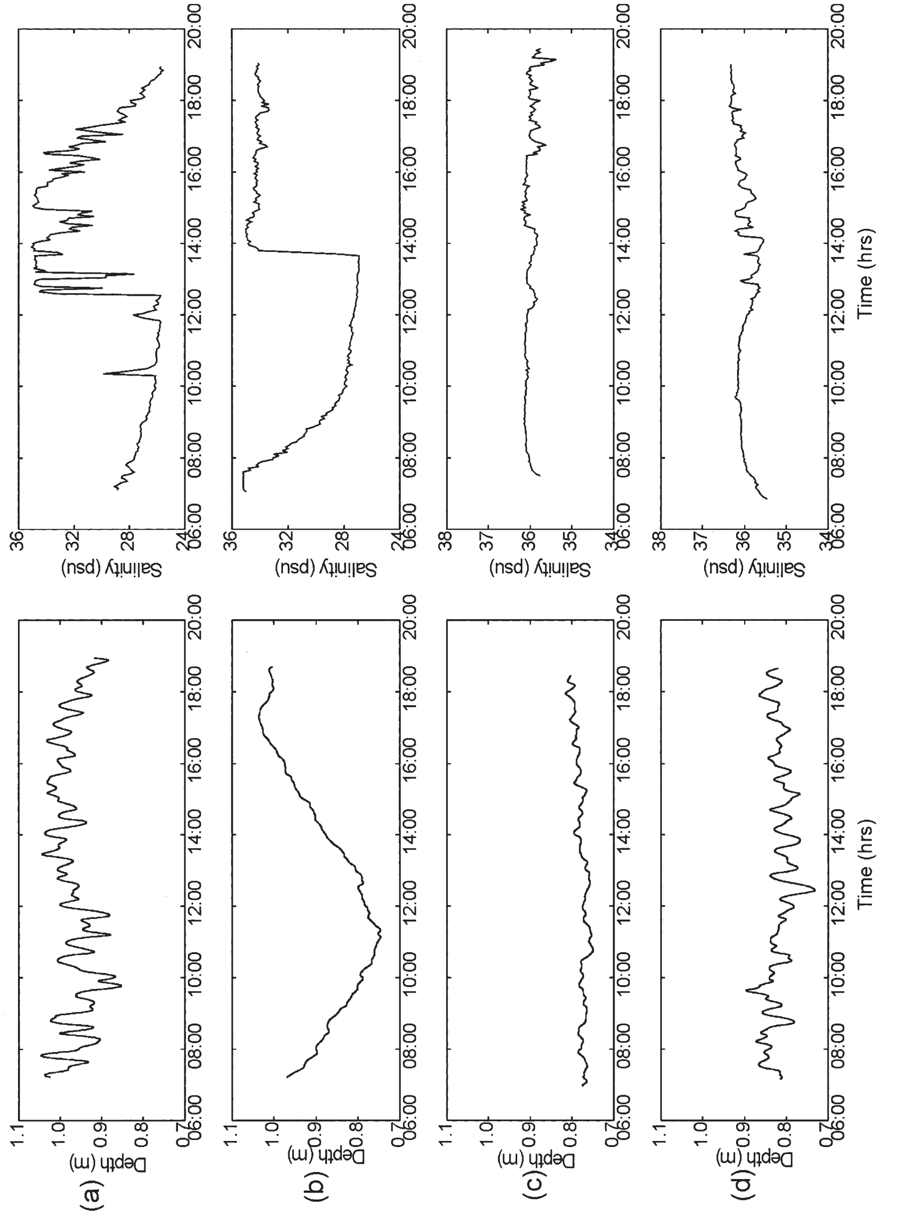

Fig. 4: Temporal variation of tidal elevation and salinity at Vassova entrance canal, during (a) 27-9-2001; (b) 3-10-2001; (c) 7-3-2002, and (d) 21-3-2002.

control over salinity was observed, with the highest values occurring during high tide (approximately 36 psu), and the lowest during low tide (approximately 27-28 psu). The highest intra-tidal salinity difference was observed during spring tidal cycles (5.1 psu during October 2001 and 3.4 psu during September 2001), and the lowest during March 2002 neap and intermediate tide (0.5 psu). Increased precipitation influenced the range of salinity values during the September and October 2001 cycle, when low salinity values (28.6 to 29.1

psu) were mostly recorded during the ebb flow. This shows the dependence of the lagoon water balance on the direct winter period precipitation.

Water quality summary statistics (nitrates, phosphates and chlorophyll-α) for all four tidal cycles are presented in Table 5, in order to define the patterns of nutrient behavior during the flood and ebb stage of the tidal period, and to identify the direction of nutrient transport at the lagoon mouth. Nitrate concentrations, during all tidal cycles, appeared at lower levels at the outer bridge (mean = 48.7 μM), than those recorded at the inner bridge (mean = 50.5 μM). The first three showed constantly high mean nitrate concentrations (47.6, 47.8 and 69.2 μM, respectively), while the 21-3-2002 tide was characterized by lower values (mean = 30.3 μM). Furthermore, it is evident that during the 7-3-2002 neap tidal cycle, higher nitrate values were observed during the ebb tidal phase, indicating the importance of nitrate transport from the lagoon to the adjacent sea during ebb tide. These higher nitrate values seem related to the fresher water entering the lagoon through seepage along the irrigation canal embankment, surrounding the lagoon from NE-N-NW.

Tidally-mean phosphate concentrations at the outer bridge of the Vassova entrance canal showed a completely opposite behavior to that of nitrates, with generally low values observed during the first three tides (0.6 μM, 0.6 μM and 1.6 μM) and significantly high values during 21-3-2002 (mean = 8.3 μM). Phosphate values were of the same order of magnitude at both bridges during the 27-9-2001 and 21-3-2002 tides, and at undetected levels at the inner bridge during the 3-10-2001 and 7-3-2002 tides. Ebb average phosphate concentration was always higher than the corresponding flood, showing that the lagoon acts as a buffer zone for the transfer of phosphorus from the adjacent agricultural plains to the Kavala Gulf coastal zone.

Table 5
Water quality characteristics at the mouth of Vassova lagoon during four different tidal cycles.

Date	Water Quality Parameter	$N\text{-}NO_3$ (μM)		$P\text{-}PO_4$ (μM)		Chlorophyll-α (μg l^{-1})	
		Outer Bridge	Inner Bridge	Outer Bridge	Inner Bridge	Outer Bridge	Inner Bridge
27-9-2001	Mean Concentration	47.6	41.3	0.6	1.1	3.6	3.8
	Max. Concentration	58.1	148.0	1.4	1.9	8.9	9.5
	Min. Concentration	24.6	8.1	0.0	0.5	0.0	0.0
	Flood Average Concentration	33.5	11.4	0.0	0.6	3.3	1.5
	Ebb Average Concentration	48.1	43.7	0.7	1.1	3.8	3.8
3-10-2001	Mean Concentration	47.8	50.3	0.6	n/a	4.0	3.4
	Max. Concentration	54.1	57.4	3.4	n/a	15.7	13.5
	Min. Concentration	41.9	46.0	0.0	n/a	0.0	0.0
	Flood Average Concentration	48.3	52.5	1.2	n/a	1.9	4.4
	Ebb Average Concentration	47.1	47.6	0.0	n/a	6.5	2.2
7-3-2002	Mean Concentration	69.2	n/a	1.6	n/a	0.7	1.1
	Max. Concentration	342.6	n/a	3.6	n/a	3.1	6.1
	Min. Concentration	0.0	n/a	0.1	n/a	0.0	0.0
	Flood Average Concentration	29.6	n/a	1.6	n/a	0.6	0.9
	Ebb Average Concentration	115.3	n/a	1.7	n/a	0.9	1.4
21-3-2002	Mean Concentration	30.3	60.0	8.3	1.1	9.9	0.2
	Max. Concentration	60.9	565.1	22.7	3.5	67.7	2.0
	Min. Concentration	0.0	0.0	3.3	0.0	0.0	0.0
	Flood Average Concentration	33.0	0.0	8.1	0.8	1.4	0.3
	Ebb Average Concentration	27.3	130.0	8.5	1.4	19.8	0.0

n/a: no data available

Chlorophyll-α depicted high values at the outer bridge during the 21-3-2002 tidal cycle (mean = 9.9 μg/l) in relation to the other periods when mean chlorophyll values of 3.6 μg/l, 4.0 μg/l and 0.7 μg/l were recorded respectively. However, these chlorophyll-α values appear higher than the corresponding concentrations observed in the adjacent coastal water. This means that the increased primary production of Vassova lagoon throughout the year is responsible for the higher ebb average chlorophyll-α values recorded at all tidal cycles (3.8 μg/l, 6.5 μg/l, 0.9 μg/l and 19.8 μg/l for the outer bridge respectively) showing that phytoplankton produced within the lagoon is transported to the coastal zone during the ebb tidal phase.

Residual Currents and Fluxes

The relative contribution of the individual flux terms to the net transport of water, salt, nitrate-nitrogen, phosphate-phosphorus and chlorophyll-α, as obtained using Eqs. (3), (4), (7) and (8) and the data recorded during the above tidal cycles, is presented in Table 6. It occurs that the Eulerian residual current V_1 has values an order of magnitude higher (mean = 0.11 m s^{-1}) than the Stokes drift effect V_2 (mean = 0.01 m s^{-1}), being negative in sign during the spring tidal cycle, thus pushing water out of the lagoon, and positive during the neap tide, thus transporting water into the lagoon. The low magnitude of the Stokes drift effect can be explained by considering that although the Stokes drift has been demonstrated to be an important mechanism in the generation of long-term residual transport in straits (DYER & KING, 1975) and channels (SYLAIOS & BOXALL, 1998), its value remains small within each individual tidal period (DYKE, 1980). A Stokes drift in the direction of the tidal wave propagation will arise when over half of the tide longitudinal velocity coincides with water levels above the tidal cycle mean (BLANTON & ANDRADE, 2001).

The higher Eulerian residual water flux was obtained during the September 2001 intermediate tidal cycle (V_1 = -0.25 m s^{-1}), when an inward Stokes drift of the order of 0.01 m s^{-1} was induced. Furthermore, one can observe that the advection of mean salinity by the residual flow of water, $V_{S,1}$, represents the main mechanism of salt flux (mean = 3.43 g s^{-1} m^{-2}) through Vassova's entrance canal in all tidal cycles. The magnitude of the residual flux of salt due to tidal pumping, $V_{S,2}$ (resulting from the non-zero correlation between the tidal oscillations in salinity and water flow) indicates that this process is also important for the salt balance of the lagoon (mean = 0.43 g s^{-1} m^{-2}). Positive values in all fluxes indicate that salt is being transported from the sea towards the lagoon, apart from the 7-3-2002 neap tidal cycle when the outward directed Stokes drift induces a negative salt flux, most probably due to the presence of non-zero correlation between water discharge and salinity.

Advection transport and Stokes drift appear of the same order of magnitude with a positive sign for the nitrate-nitrogen flux (mean $V_{N,1}$ = 78.19 μg s^{-1} m^{-2}; mean $V_{N,2}$ = 37.23 μg s^{-1} m^{-2}) during the first two cycles, following

Table 6
Residual currents and fluxes of water, salt, nitrogen, phosphorus and chlorophyll-α during four tidal cycles at Vassova lagoon entrance canal.

Date	Water Flux (m/s)		Salt Flux (g s^{-1} m^{-2})		Nitrate Nitrogen Flux (μg s^{-1} m^{-2})		Phosphate Phosphorus Flux (μg s^{-1} m^{-2})		Chlorophyll-α Flux (μg s^{-1} m^{-2})	
	V_1	V_2	$V_{S,1}$	$V_{S,2}$	$V_{N,1}$	$V_{N,2}$	$V_{P,1}$	$V_{P,2}$	$V_{CHL,1}$	$V_{CHL,2}$
27-9-2001	-0.25	0.01	-7.05	0.57	-149.8	2.41	-4.12	-4.68	-0.82	0.30
3-10-2001	-0.10	0.04	-1.72	1.16	-24.83	1.68	-3.90	9.26	-0.15	-1.05
7-3-2002	0.12	0.001	4.60	-0.01	131.4	137.4	6.92	-2.67	0.09	0.12
21-3-2002	0.004	0.007	0.38	0.005	6.78	-7.46	4.09	12.49	0.15	-2.27

the influence of the Eulerian residual current. Behavior similar to nitrogen was also shown by phosphate-phosphorus, with almost equal material transport mechanism (mean $V_{P,1}$ = 4.75 μg s^{-1} m^{-2}; mean $V_{P,2}$ = 7.27 μg s^{-1} m^{-2}). The Eulerian residual transport of chlorophyll-α had a mean Eulerian transport of 0.30 μg s^{-1} m^{-2} and a mean Stokes drift effect of 0.93 μg s^{-1} m^{-2}.

Tidal Prism and Flushing Time Estimation

The calculated values of local water prisms during flood, ebb and the whole tidal period, obtained by solving Eqs. (10) and (11), for the Vassova lagoon are given in Table 7. Mean local water prism during flood was of the order of 4,218 m^3 per meter of channel width, with increased values obtained under spring tidal conditions (3-10-2001). Mean local water prism during ebb was found as 6,573 m^3 per meter of channel width, with reduced volumes obtained under neap tidal conditions (7-3-2002). Tidal prism varied from –10,417 to +2,948 m^3 per meter of channel width. Since the entrance canal is approximately 11 m wide, it occurs that a mean tidal exchange of 43,477 m^3 was recorded during all four tidal cycles, with corresponding values of 114,588 m^3, 24,171 m^3, 32,433 m^3 and 2,715 m^3 respectively. Since the Vassova lagoon has a volume of 7 × 105 m^3, it occurs that tidal exchange corresponds to 16.4%, 3.5%, 4.7% and 0.4% of the total lagoon volume, respectively, with a mean value of 6.25%.

Flushing times were computed according to DYER (1973) and were found to range from 5 to 14 days, depending on tidal status and freshwater runoff. Neap tidal conditions and nearly zero freshwater discharge produced the highest flushing time. On the contrary, spring tide and precipitation appear as the main factors for ebb tidal volume increase, during the 27-9-2001 and 3-10-2001 tidal cycles, thus increasing net tidal prism and reducing the lagoon flushing time to approximately 5 days.

Conclusions

The physical processes controlling water, salt and nutrients transports during the lagoon-shelf exchanges are primarily influenced by tidal variability, lagoon mouth configuration, lagoon size and orientation to the prevailing wind directions, freshwater discharge, bottom topography and mean depth. Variability of these fluxes determines lagoon flushing rates and residence times and influences water quality and biogeochemical processes within the lagoon.

This study presented a methodology, which can be used to estimate fluxes of water, salt, nutrients and chlorophyll-α in and out of a lagoon, and also identified the source (i.e., from the lagoon or from the sea) and main mechanisms of constituent transport. Results from four representative tidal cycles showed that tidal flood (2.6 to 9.3 hrs) exceeded in duration tidal ebb (3.25 to 5.0 hrs) under spring and neap tidal conditions. Ebb tidal currents were stronger in magnitude than the flood, especially under neap tidal conditions, with maximum flow occurring almost 1 hr before maximum tidal fall. Unstable conditions characterized the temporal variation of longitudinal and lateral velocity, inducing as expected a rightward deflection on flood or ebb flow. Nutrient intra-tidal variability showed strong seasonal dependence, with higher values

Table 7
Local water prisms during flood, ebb and the whole tidal period at the mouth of Vassova lagoon.

Date	V_{Flood} (m^3 m^{-1})	V_{Ebb} (m^3 m^{-1})	V_{Prism} (m^3 m^{-1})	V_{Prism} / V_{Lagoon} (%)	Flushing Time (d)
27-9-2001	1,690	12,107	-10,417	16.4	5.3
3-10-2001	7,819	10,016	-2,197	3.5	4.2
7-3-2002	3,980	1,032	2,948	4.7	13.7
21-3-2002	3,386	3,139	246	0.4	10.7

during September, October and early March, and lower during the late March period. A reverse behavior was shown in the variability of phosphates.

Analysis of residual fluxes into a Eulerian and a mass transport Stokes drift mechanism illustrated that the advective water and dissolved properties (salt, nitrates, phosphates and chlorophyll-α) fluxes appeared an order of magnitude higher than tidal pumping, pushing water and dissolved constituents into the lagoon under neap tidal conditions and out of the lagoon during spring tides. This Eulerian residual flow essentially quantifies the net result of freshwater outflow (during September and October), the long period wind driven transport and the other non-tidal flow in response to Vassova lagoon – Kavala Gulf exchanges.

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