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Salt-wedge propagation in a Mediterranean micro-tidal river mouth

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ABSTRACT

The dynamics of a seasonally formed salt-wedge propagating along the micro-tidal channel of Strymon River estuary, Northern Greece, and its consequences on river water quality, are thoroughly studied through intensive sampling campaigns. The wedge is developed at the downstream river part, under the summer limited freshwater discharge conditions ($Q < 30\ m^3/s$). The geometric features of the wedge (length and thickness) appeared directly related to Strymon River discharge. A maximum intrusion length of 4.7 km along Strymon River estuary was observed under minimum river discharge of almost $6\ m^3/s$. Relations produced from *in situ* data illustrate that limited river flow expands the wedge horizontally, reducing its vertical dimension, while higher flows lead to increased wedge thickness. Estuarine flushing time ranges between 0.2 and 1.5 days, exponentially dependent on Strymon River discharge. Wedge velocities depicted tidal asymmetry between tidal phases, with consistent inward motion, even under the ebb tidal stage. Strong vertical stratification prevails throughout the tidal cycle, proving the limited vertical mixing between the two layers, although higher interfacial stresses are produced in ebb. Bottom topography plays an interesting role in wedge propagation, as the presence of an underwater sill either prevents saline intrusion during flood or isolates the front of the wedge from its core at the ebb. Ecological consequences of salt-wedge propagation in Strymon River estuary are the frequent evidence of bottom hypoxic conditions and the increased TSS levels, leading to the occurrence of a turbidity maximum at the tip of the salt-wedge. Higher BOD and ammonium levels were mostly observed at the river end, associated to point and non-point pollution sources. Nitrates and silicates were found associated with freshwater fluxes, while ammonia levels were related to saline intrusions. The reduced phosphorus freshwater fluxes, resulting from phosphorus uptake at the upstream reservoir (Kerkini Lake) and the increased bottom turbidity induced by the salt-wedge seem responsible for the limited chlorophyll-*a* levels along Strymon River estuary.

1. Introduction

Estuarine dynamics are controlled by riverine factors (river discharge), marine factors (tides, waves and currents), meteorological factors (winds and atmospheric pressure variability) and geomorphologic factors (topography, bathymetry) (Sierra et al., 2002). The variation of these controlling factors is used to define classes (from well-mixed to highly stratified) and delineate the type of circulation and the related salinity structure characteristics (Hume et al., 2007). The development of a salt-wedge requires a relatively deep river channel and a micro-tidal environment (tidal range less than 2 m), leading to the absence of tide-induced turbulence, in which the strong density stratification is maintained by high river discharge (Geyer and Farmer, 1989). A more complex description identifies two types of salt-wedge estuaries, based on the determinant factor of river discharge (Ibáñez et al., 1997). In the first type, a salt-wedge regime is established during low river flows, whereas during high flows the wedge is washed away and the estuary turns into a river (as in Ebro River and Rhone River). In the second type, a salt-wedge is established during high river flows, whereas a partially mixed estuary develops during low flow conditions (as in fjords) (Ibáñez et al., 1997).

In the Mediterranean micro-tidal environment, salt-wedge intrusion along rivers is a natural phenomenon, although may depend on factors susceptible to natural and man-made changes, such as the river mouth configuration and the freshwater inputs (van der Tuin, 1991). River mouth configuration changes may involve bathymetric and bottom slope modifications, as a result of sediment transport from river floods and storm surges, but mostly on hydraulic works, thus allowing or preventing salt- water intrusion upstream the estuarine channel (Graas and Savenije, 2008). Freshwater flow changes may occur by natural factors

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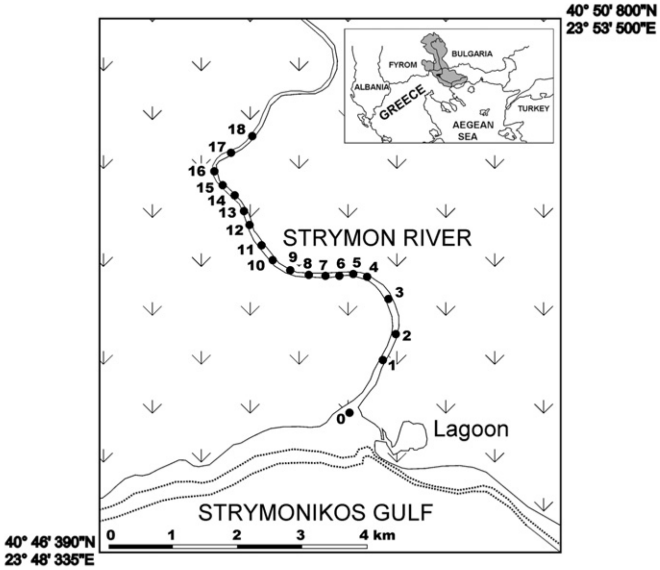

Fig. 1. The transboundary Strymon River catchment area and the location of monitoring stations along the River lower reaches.

(precipitation and runoff change of drainage basin) and mostly by human development activities (freshwater flow regulation from upstream reservoirs). In micro-tidal estuaries, river discharge plays the dominant role controlling the development and the advance or retreat of a salt-wedge. Increased levels of river flow tend to move the salt-wedge towards the ocean, while during periods of low freshwater discharge the salt-wedge tends to intrude for rather long distances upstream.

The steady form of the salt- wedge in a micro-tidal sea is the 'arrested salt-wedge' (Chanson, 2004). Its mean position along the estuarine channel is determined by a balance between the driving baroclinic pressure gradient due to longitudinal density difference and the retarding force induced by the opposing river flow (D'Adamo and Lukatelich, 1985). Under these conditions, a sharp boundary within the water column is developed, separating the upper less salty layer from the intruding wedge-shaped salty bottom layer. This interface follows the general shape of the wedge, thus increasing in depth in the upstream direction (Rattray and Mitsuda, 1974).

The salt-wedge plays an important role in the distribution of chemical and biological variables, and their effect on water quality (Stephens and Imberger, 1996). Bottom hypoxic and/or anoxic events may be associated to the limited vertical mixing between the surface and bottom layers (Douglas et al., 1996), inducing changes in sediment redox and bottom nutrient and metal release rates (Douglas and Adeney, 2000). Moreover, salt-wedge intrusion appears to control the estuarine supply of inorganic nutrients, the levels of light, temperature and turbidity, thus regulating the spatial and temporal characteristics of phytoplankton distribution (Yin et al., 1995; Thompson, 2001; Twomey and John, 2001; Marcelo Acha et al., 2008; Kasai et al., 2010). All of these changes affect organisms that live within or pass through the estuary, especially benthic organisms and fish.

For the above reasons, the dynamics of a seasonally formed salt wedge, propagating along the micro-tidal mouth of Strymon River, Northern Greece, deserve special attention. Similar conditions exist at the lower reaches of several Greek rivers, but published reports are limited to Louros River (Scoullos et al., 1996) and Acheloos River (Dassenakis et al., 1997). In this paper, observations of physical and chemical parameters obtained during intensive field campaigns along the lower Strymon River are used to study the influence of seasonal discharge reductions on the salt-wedge dynamics.

2. Materials and methods

2.1. Site description

Strymon is a transboundary river of Greece, Bulgaria and FYROM, with a total channel length of 392 km and a total drainage area of 13,330 km^2, 36.4% of which belongs to Greek territory (Antonopoulos et al., 2001) (Fig. 1). The river enters Greece in a NW–SE direction, with a mean annual discharge of 59.5 m^3/s, having strong seasonal variability, ranging on the average from 18 m^3/s in August to 122 m^3/s in April. The river passes Kerkini Lake, a man-controlled artificial reservoir located 77 km upstream of its mouth; as a result its flow diminishes downstream of the dam, especially during the irrigation period (March to September), from near zero to 20 m^3/s. After flowing through Serres plain, the river outflows into Strymonikos Gulf in the North Aegean Sea (Fig. 1).

Recent findings suggest that the total freshwater input of Strymon River to the Gulf has been reduced by approximately 30%, compared to previous decades, due to extensive irrigation and reduced precipitation in the area (Sylaios et al., 2006). Such hydrologic regime alteration leads to significant changes in the Strymonikos Gulf coastal circulation and renewal (Sylaios et al., 2006), the biogeochemical cycling of nutrients (Sylaios and Tsihrintzis, 2009), and the structure of food web (Koutrakis et al., 2004), while it favours the occurrence of a salt-wedge intruding upstream the estuary (Haralambidou et al., 2005). Seawater easily intrudes into the river, since the riverbed is lower than the sea surface up to approximately 8 km upstream from the river mouth.

Table 1
Field monitoring program at Strymon River estuary, in accordance to river discharge and tidal status. n.d: no data available.

Date	Sampling type	Survey upstream river end (km)	River discharge (m^3/s)	Tidal range (m)
30 Apr 2003	Temporal (anchored at station 2) and 1 up-estuary transect	8.1	78[a]	n.d
21 Jun 2003	1 up-estuary transect	3.0	n.d	0.10
05 Jul 2003	4 up-estuary transects	3.8	54.3	n.d
17 Jul 2003	3 up-estuary transects	6.2	6.1	0.10
22 Aug 2003	3 up-estuary transects	4.4	29.6	0.07
31 Aug 2003	4 up-estuary transects	4.6	31.8	0.10
16 Jul 2004	3 up-estuary transects	6.1	18.9	0.10
25 Jul 2004	3 up-estuary transects	6.1	29.4	0.07
31 Jul 2004	3 up-estuary transects	5.1	22.7	0.13
18 Aug 2004	4 up-estuary transects	4.6	34.0	0.13
28 Aug 2004	4 up-estuary transects	4.1	48.9	0.14

[a] Data provided by Kerkini Lake Management Authority.