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# ZMAJEVO OKO – A UNIQUE EXAMPLE OF ANCHIALINE SYSTEM ON THE ADRIATIC COAST (CROATIA) DURING SPRING-SUMMER STRATIFICATION AND AUTUMN MIXING PERIOD

**ELVIRA BURA-NAKIĆ*, MARIJA MARGUŠ, SANDI ORLIĆ & IRENA CIGLENEČKI**

Ruđer Bošković Institute, Bijenička 54, 10 000 Zagreb

Zmajevo oko is a naturally eutrophicated saline lake situated on the Gradina Peninsula, close to the village of Rogoznica on the central Dalmatian coast. Since 1992 the Lake has been intensively studied and in 2011 hydrographic and water column stratification in relation with reduced sulfur species and microbial activity was investigated during two different seasons: the spring-summer stratification and autumn mixing period.

**Key words:** Zmajevo oko, stratification, anoxia, sulfide, anchialine

## INTRODUCTION

Zmajevo oko is a unique and extreme type of euxinic aquatic environment on the Mediterranean coast with all the features that are well known from the largest world anoxic systems like the Black Sea, Framvaren Fjord and Lake Pavin. It differs from other well-characterized anoxic basins in respects to geomorphologic and hydrological characteristics including the relative small size and very easy access to the anoxic water layer, which usually exists below 9 m in depth. The lake has very restricted water exchange with the surrounding sea through porous carbonate rocks and mixing of the lake waters is strongly influenced by meteorological conditions, and rainfall with surface runoff through the porous karst are the only source of freshwater inflow. The incomplete mixing of the lake water occurs every year in the late fall or winter when cold oxygen-rich water sinks downward. In consequence of lake water mixing, nutrient over-enrichment of the entire water column occurs, since the nutrient-rich bottom water is mixed throughout the water column supporting new phytoplankton and oxygen production in the oxic water layer. Regarding basic geochemical, hydrological and geomorphological characteristics Zmajevo oko can be considered one type of anchialine system.

Since 1992 the Lake has been intensively studied through the monitoring of seasonal variations of hydrological conditions, distribution of dissolved oxygen, nutrients, dissolved organic carbon (DOC), surface-active substances (SAS), reduced sulfur species (RSS), phyto- and zooplankton in water column of the Zmajevo oko (CIGLENEČKI *et al.*, 1996, 1998, 2005; ĆOSOVIĆ *et al.*, 2000; BURA-NAKIĆ *et al.*, 2009). In the present paper the main physico-chemical and microbiological characteristic of the Lake during the spring-summer stratification and autumn mixing periods in 2011 will be presented.

* ebnakic@irb.hr

## MATERIALS & METHODS

Electrochemical determinations of total reduced sulfur species (RSS) were made by cathodic stripping linear sweep voltammetry (CSLSV) in unfiltered samples (CIGLENEČKI *et al.*, 1996; CIGLENEČKI & ĆOSOVIĆ, 1997; BURA-NAKIĆ *et al.*, 2009). Dissolved organic (DOC) and particulate organic carbon (POC) were determined by the use of high-temperature catalytic oxidation (HTCO) as reported previously (CIGLENEČKI *et al.*, 2005). Temperature, salinity and dissolved oxygen concentration were recorded by CTD probe (Hach Lange HQ40D).

Microbiological activity in the lake was determined by fluorescence microscopy (IVANČIĆ *et al.*, 2010).

## RESULTS AND DISCUSSION

Profiles of salinity and temperature recorded in 2011 are similar to those reported previously in the lake for the same seasons (CIGLENEČKI *et al.*, 2005; BURA-NAKIĆ *et al.*, 2009) (Figs. 1a-d). Thermohaline stratification of the lake was stable through the spring-summer of 2011, while in autumn 2011 the breakdown of stratification occurred and holomictic conditions were established. Holomictic conditions were followed by the appearance of anoxic conditions in the whole water column similar

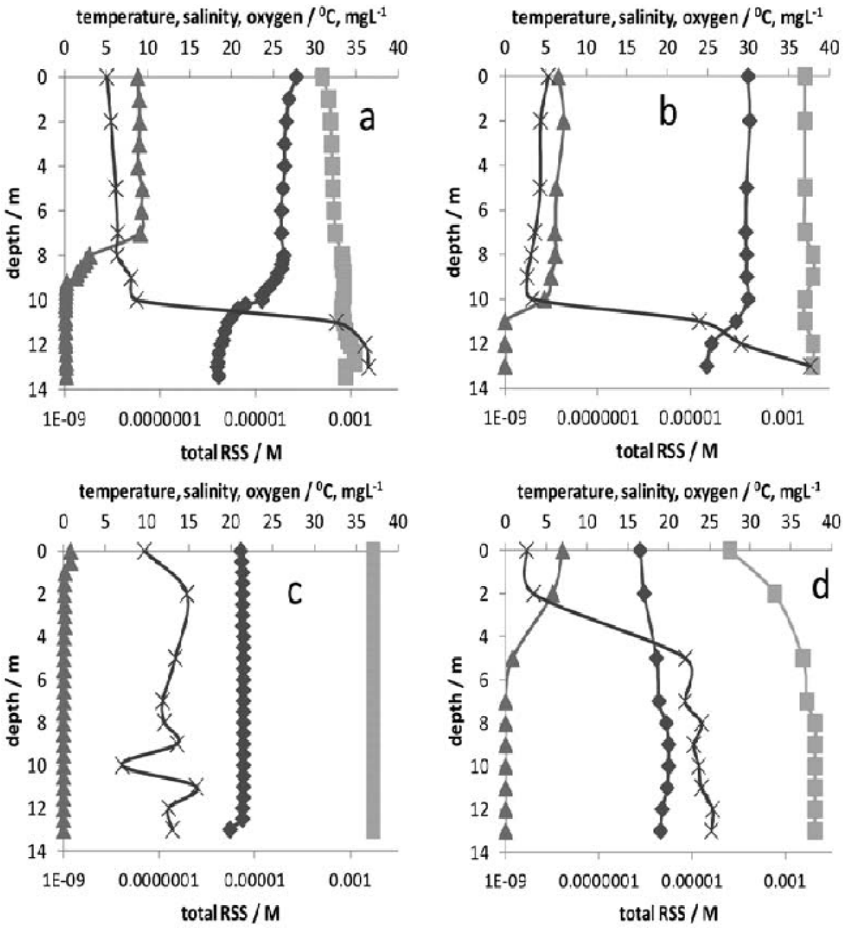


**Fig. 1.** Salinity (■), temperature (◆), oxygen (▲) and RSS (×) profiles for: June (a), August (b), October (c) and December (d) 2011.

**Fig. 2.** Image of Zmajevo oko surface during sampling in: March (a) and October (b) when surface of the Lake was milky white in color due to the water layer mixing.

to those recorded in September 1997, Fig. 2 (CIGLENEČKI *et al.*, 2005). The appearance of complete anoxia in October 2011 we believe to be caused by meteorological conditions i.e. a very dry and unusually warm summer which was followed by cold and dry early autumn. The first weekend in October 2011 was characterized by a very rapid change of temperature, of 15 C° in less than 24 hours, which caused cooling of the very dense surface layer and its subsequent rapid descent to the bottom. The lake cooling followed by pycnocline dissolution leads to upward transport of reduced sulfur species from the bottom to the surface. The considerable release of reduced sulfur species causes oxygen depletion owing to oxidation and then the appearance of anoxia in the whole water column. Rainfall and lower air temperatures in October and November 2011 caused new autumn/winter thermohaline stratification as recorded in December 2011 (Fig. 1d).

During the spring-summer stratification period concentrations of dissolved oxygen decreased slowly with depth and anoxic conditions were recorded at depths higher than 8 m (Figs. 1a and b). The anoxic water layer is characterized by high concentrations of RSS (up to the $10^{-3}$ M) mainly in the form of sulfide, as reported previously (CIGLENEČKI *et al.*, 2005; BURA-NAKIĆ *et al.*, 2009). The autumn mixing period is characterized by a lower concentration of RSS (~$10^{-7}$ M) mainly in the form of elemental sulfur and/or polysulphide.

Regarding microbiological activity Zmajevo oko represents a highly productive chemotrophic system. The number of bacteria was always higher than $10^6$ cell/L. The water column stratification is largely responsible for the strong microbiological stratification and activity. In the investigated period, high activity of the green sulfur phototrophic bacteria *Chlorobium* sp. was found.

## CONCLUSION(S)

All the characteristics outlined above such as: 1) stable and constant oxic/anoxic interface; 2) stratified system that has persisted long enough to produce steady--state conditions relative to sulfide concentrations; 3) no surface connection with the sea; 4) basin field with salt or brackish water, which fluctuates with the tides, make Zmajevo oko an ideal site to examine the processes that control the biogeochemistry

of anoxic anchialine environments. The small size and physically stable nature of Zmajevo oko allows researchers to examine small-scale spatial and temporal variability as well as longer term processes.

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