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WATER AND TEMPERATURE DYNAMICS IN THE ANCHIALINE CAVE JAMA POD ORLJAKOM IN THE FUNCTION OF THE RECENT INTRODUCTION OF INVASIVE SPECIES FICOPOMATUS ENIGMATICUS (ANNELIDA, POLYCHAETA)

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The invasive species *Ficopomatus enigmaticus* (Annelida, Polychaeta) colonized the anchialine cave Jama pod Orljakom (Krka River estuary, Croatia) seven years ago. This study examines the thermal regime of the cave and its water connection to the estuary. The results show that the cave is well connected to the Krka River estuary, but despite the good connectivity, limited water exchange can occur – especially in the surface layer. Since levels of dissolved oxygen and rates of food supply are heavily influenced by the water exchange rates, a weak exchange can determine limiting conditions on the growth and population density of *F. enigmaticus* in the cave.

Key words: anchialine cave; *Ficopomatus enigmaticus*; water temperature; water level; water exchange; tidal analysis

INTRODUCTION

The anchialine cave Jama pod Orljakom is located in Cretaceous limestone 50 m from the estuarine coast in the lower Krka River estuary. The cave is 23 m deep and 90 m long with two pools, 3.5 and 7 m of depth (CUKROV *et al.*, 2010b).

Ficopomatus enigmaticus (Fauvel, 1923) belonging to the polychaete family Serpulidae is recorded worldwide and inhabits coastal brackish waters, lagoons and estuaries of warm temperate areas. On any hard substrate, this serpulid tubeworm builds calcareous tubes with distinctive collar-like rings at irregular intervals, so it is relatively easy to identify. It is an efficient suspension-feeder, very tolerant and physiologically well adapted to temperature and salinity variations, eutrophic conditions and low dissolved oxygen content. The first records of *F. enigmaticus* in anchialine caves were recently reported from karstic caves of Sardinia and Croatia (MANCONI, 2009; MANCONI *et al.*, 2010; CUKROV *et al.*, 2010a).

F. enigmaticus invaded the Krka River estuary most probably eight years ago presumably by ballast water. One year later *F. enigmaticus* was recorded in the anchialine cave Jama pod Orljakom. Due to fast invasion by this tubeworm in the latter anchialine cave, it was necessary to investigate water connection between the

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cave and the estuary to understand the environmental conditions favoring the colonization process.

The knowledge of salt and heat transport processes and the estimation of tidal dynamics are basic for the definition of the type and intensity of the water connection between the cave and the estuary. We analyzed two parameters that represent these processes: temperature *in situ* and water levels. The analysis provided direct information on thermal conditions in the cave and water dynamics between the estuarine and anchialine systems. In the future, this approach will also serve to help develop and validate the inverse methodology (KLANJŠČEK *et al.*, 2012) utilizing benthic sessile organisms, such as *F. enigmaticus*, as bioindicators to estimate the level of water connection, and its effects.

METHODS

Temperature was measured at multiple depths in the cave Jama pod Orljakom during approximately two years (April 2010 – February 2012), and seven months (July 2011 – February 2012) in the estuary. Water levels were measured in the cave (March 2011 – February 2012) and in the estuary (July 2011 – February 2012). Parameters were measured by HOBO (Onset) and SENSUS ULTRA (ReefNet) data loggers. Spectral density analysis (EMERY & THOMSON, 1998) on temperature and water levels was performed using multitaper method (PERCIVAL & WALDEN, 1993) to estimate total variance of the oscillatory signal over the whole frequency spectrum. The relationship between the measured time series was estimated using biased autocorrelation and cross-correlation (ORFANIDIS, 1996), and the square of the signal coherence was calculated (HAYES, 1996; Signal Processing Toolbox, Matlab2011b). Signal was filtered into high frequency (HF) and low frequency (LF) signals using an order 6 Butterworth filter with normalized cutoff at a 40 hour period. Major diurnal (O1, P1, K1) and semi-diurnal (N2, M2, S2, K2) tidal harmonics of the HF water level signal were extracted by using T_TIDE Toolbox (GODIN, 1972; PAWLOWICZ *et al.*, 2002). Yearly sinusoidal fluctuation has been fitted to the LF temperature measurements to analyze the seasonal cycle (Curve Fitting Toolbox, Matlab2011b).

RESULTS AND DISCUSSION

Values of water level measurements in the cave and in the estuary were almost identical, with the tidal range of approximately 84 cm. Water levels in the cave lagged less than 15 min behind those of the estuary. The water level showed greater variability in the estuary: variance in the estuary was 5.23% higher than in the cave. For each time series, the variance was equally distributed for LF oscillations (42.38–43.94%) and HF oscillations that include tidal oscillations (56.06–57.02%).

The cave water levels presented 20.51% less variance from March to July 2011 than from July 2011 to February 2012. The reduction of variance was mainly due to the attenuation of variance in LF oscillations (57.24%), while the variance associated with an HF signal did not change significantly. This indicates that the difference in water level time series captured during different periods will be primarily driven by the physical and environmental forcing at low frequencies, such as meteorological conditions and the River Krka flow. At both locations, extracted diurnal and

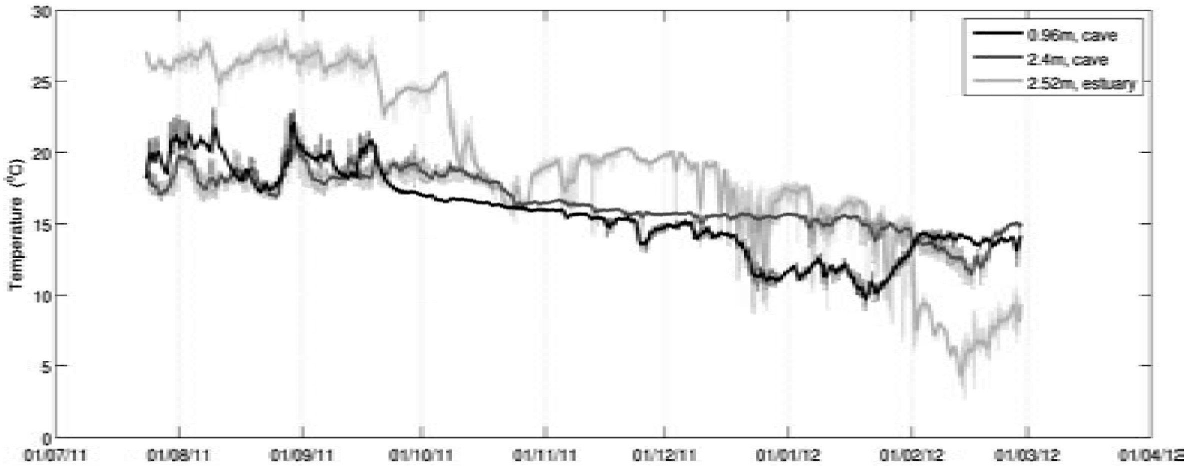

Fig. 1. Extracted LF temperature signal (thick lines) from measured temperature values (thin lines) in the cave Jama pod Orljakom and Krka River estuary during the period July 2011–February 2012

semidiurnal tidal constituents contribute approximately 90.7–91.9% variance to the HF signal.

The measured temperature signals show the expected seasonal sinusoidal oscillation (Fig. 1). The estuary temperature signal exhibits the highest amplitude of the sinusoid, while the amplitudes in the cave are significantly smaller. The difference shows that the mechanisms of communication between the estuary and the cave damp the estuarine temperature forcing. Temperature measurements during the period July 2011-February 2012 indicate that the temperature range is two, and variance 4.42–10.07 times greater in the estuary than in the cave (Fig. 1, Tab. 1). In

Tab. 1. Variance, range and mean temperature values of measured data in the cave Jama pod Orljakom and Krka River estuary.

	location	**var(t_T)** ($^oC^2$)	**min(t_T)** (^oC)	**max(t_T)** (^oC)	**mean(t_T)** (^oC)
	0.96m, cave	8.6483	8.9400	23.2000	15.6856
	2.40m, cave	3.8122	10.4500	22.5000	16.4956
Jul 2011 - Feb 2012	2.52m, estuary	38.3774	2.6500	28.7600	19.1953
	0.10m, cave	4.4330	9.3600	20.7700	13.7547
	0.50m, cave	5.6908	10.5200	21.6300	14.5698
	0.78m, cave	5.7698	12.2800	22.6000	16.3327
	1.25m, cave	4.8832	13.0200	22.8200	16.5789
	1.30m, cave	4.5897	12.8800	22.9100	16.3109
	1.67m, cave	3.2797	13.3400	23.0200	16.4634
	2.07m, cave	1.6990	13.5200	22.3800	16.3662
Mar 2011- Jul 2011	3.00m, cave	1.4776	13.4000	21.4100	16.0729

the cave, the temperature range and variance of the surface water layer is higher than in the lower water layers because the cave microclimate and precipitation dynamics strongly influence the surface layer. The estuary has the highest average temperature, whereas in the cave average temperature increases with depth (Tab. 1).

The results show that the cave is well connected to the Krka River estuary. Despite the good connectivity, the temperature profile of the cave indicates limited mixing in the water column within the cave and, therefore, a limited water exchange especially in the surface layer.

CONCLUSIONS

Our analyses show the utility of temperature and water level measurements obtainable by inexpensive consumer-grade sensors. Relatively long time series enable comprehensive analysis of tidal signals; seasonal signals can also be captured, but even longer time series, possibly with lower sampling rate, would be greatly beneficial. To estimate physicochemical properties of the cave comprehensively, the monitoring of environmental parameters can be combined with observations of the biota focusing on both composition/structure of the benthic fauna and population density of *F. enigmaticus* to evaluate potentialities of these organisms as bioindicators of environmental quality in anchialine caves.

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