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Temperature as a tracer of hydrological dynamics in an anchialine cave system with a submarine spring

David Domínguez-Villar [1,2] · Neven Cukrov [1] · Kristina Krklec [3]

Abstract
Although temperature is a nonconservative tracer, it often provides useful information to understand hydrological processes. This study explores the potential of temperature to characterize the hydrological dynamics of a submarine spring and its coastal karst aquifer in Krka Estuary (Croatia). The estuary is well stratified and its water column has a clear thermocline. A network of loggers was designed to monitor the temperature along vertical profiles in the estuary and the coastal aquifer, taking advantage of an anchialine cave that enabled access to the subterranean estuary. The location of the thermocline in the groundwater, which defines the upper boundary of the saline intrusion, depends on (1) the recharge of the aquifer via infiltration of precipitation, (2) the evolution of the thermocline in the estuary, and (3) the tidal oscillations. The sources of water flowing though the anchialine cave were identified: brackish water from the estuary above the thermocline, saline water from the estuary below the thermocline, and freshwater from infiltrated precipitation. A conceptual model is described that characterizes the hydrological dynamics of this coastal aquifer and its interactions with the estuary. Thus, at least for some hydrological settings, temperature is a valid tracer to characterize the main hydrological processes. The measurement of temperature is inexpensive compared to other (conservative) tracers. Therefore, for those hydrological settings that have water masses with distinct temperatures, the use of temperature as a tracer to establish conceptual models of the hydrological dynamics is encouraged.

Keywords Anchialine cave · Temperature · Submarine spring · Subterranean estuary · Croatia

Introduction

Groundwater is the main hydrological resource in carbonate regions due to fast infiltration of rainfall in these rocks (Jukić and Denić-Jukić 2004). The inhabitants and the ecology of these regions greatly depend on access to underground freshwater. The quality of the water is a limiting factor for many uses for humans, animals and plants. In coastal carbonate regions, where seawater interacts with freshwater aquifers, groundwater often has high salinity, preventing its use for

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human consumption and other uses (e.g., Arfib et al. 2006; Fleury et al. 2008; Werner et al. 2013). Hydrogeological studies in coastal regions often use data from wells (Smith et al. 2008; Nakada et al. 2011; Perriquet et al. 2014), although absence of wells is common in remote karst areas or in sites where significant salt-intrusion problems are associated with the coastal aquifer. In these cases, submerged coastal caves provide direct access to the aquifer (e.g., Beddows et al. 2007). An anchialine cave is a cave completely or partially submerged and that is under the influence of seawater (Stock et al. 1986; Bishop et al. 2015); thus, anchialine caves provide a great opportunity to study the dynamics of coastal karst aquifers.

Springs occur where groundwater flows out from bedrock to the surface in discrete locations. In coastal karst aquifers, springs often occur under sea level (e.g., Drogue and Bidaux 1986; Swarzenski et al. 2001; Fleury et al. 2007; Bayari et al. 2011; Surić et al. 2015). These submarine karst springs are also known as vruljas (Bögli 1980; Bonacci 1987); however, along coastal areas, the discharge of freshwater from the aquifer is often diffuse rather than concentrated. These wide

underground zones where saline and fresh groundwater masses interact are known as subterranean estuaries (Moore 1999). Subterranean estuaries are often affected by tides providing additional complexity to the hydrological dynamics of these systems (Abdullah et al. 1997; Beddows 1999; Robinson et al. 2007); thus, due to the variable hydrological and chemical dynamics of submarine estuaries, anchialine environments are a particularly interesting ecological niche (Iliffe 2000), and are the site where a variety of geological processes such as dissolution, dolomitization, or precipitation of calcite/aragonite take place (Csoma et al. 2006; Palmer 2007). The hydrology along the coastline of estuaries is even more complex, due to the mixture of brackish water from the estuary, freshwater from the continental aquifer and the seawater (Valle-Levinson 2010).

Temperature is a powerful tool to trace hydrological processes (Anderson 2005; Rau et al. 2014) and has been used to study the dynamics of rivers (Silliman et al. 1995; Hebert et al. 2011; Fullerton et al. 2015), inter-tidal environments (Gunawarfhana and Kazama 2009; Befus et al. 2013), aquifers and springs (Taniguchi 1993; Sinokrot and Stefan 1993; Genthon et al. 2005; Gabrovšek and Turk 2010). Although temperature is a nonconservative parameter (Luhmann et al. 2015), it still can provide useful qualitative information on the hydrological processes of a system, especially when studying short-term periods that limit the impact of certain thermal controls (e.g., seasonal temperature variability of some water masses and precipitation). However, the use of temperature to characterize the hydrological dynamics in submerged springs is still limited (Mejías et al. 2012). In estuaries and subterranean estuaries, the interaction of fresh and salty waters often results in a vertical stratification of both water masses that have different salinity, chemistry and temperature values. The transition between these water masses is characterized by a sharp vertical gradient in those parameters that is often referred to as a halocline, chemocline and/or thermocline (Beddows et al. 2007; Gunawarfhana and Kazama 2009; Garman et al. 2011; Torres-Talamante et al. 2011; Menning et al. 2015).

In order to evaluate the potential of temperature to trace hydrological dynamics in complex subterranean estuary locations, an anchialine cave in Krka Estuary (Croatia) was monitored. This is a particularly interesting case because the cave entrance also functions as a submarine spring or vrulja. The region is characterized by micro-tides that affect the estuary (Legović 1991; Vilibić and Orlić 1999; Cushman-Roisin and Naimie 2002; Mihanović et al. 2006). Since Krka Estuary is well stratified and has a clear thermocline (Legović et al. 1991a, b; Orlić et al. 1991), a network of loggers was designed to characterize the evolution of the thermal vertical profile along different locations of the hydrological system. Thus, the aim of this research is to test whether temperature can be used to identify the main controls dominating the hydrological dynamics of complex coastal karst systems. Electrical conductivity or other

conservative parameters would describe better the interactions of water masses in a subterranean estuary; however, temperature loggers are much more affordable than those that measure conductivity or other conservative parameters, and still provide important information on the evolution of the systems (e.g. Beddows et al. 2007; Befus et al. 2013; Perriquet et al. 2014). Therefore, the motivation of this study was to show the potential that the relatively inexpensive monitoring networks of temperature loggers have to characterize the dynamics of coastal aquifers, in order to promote the implementation of similar investigations among a wide range of scientists interested in coastal karst environments.

Regional setting

This research focuses on an anchialine cave (43.78°N; 15.83°E) and its interaction with Krka Estuary in Croatia (Fig. 1). The site is located in the centre of the Dalmatian
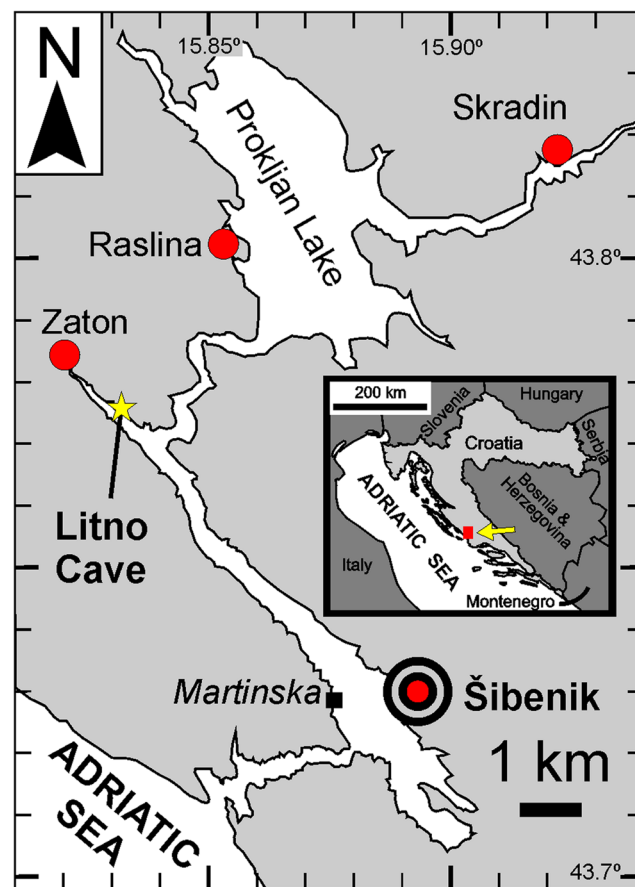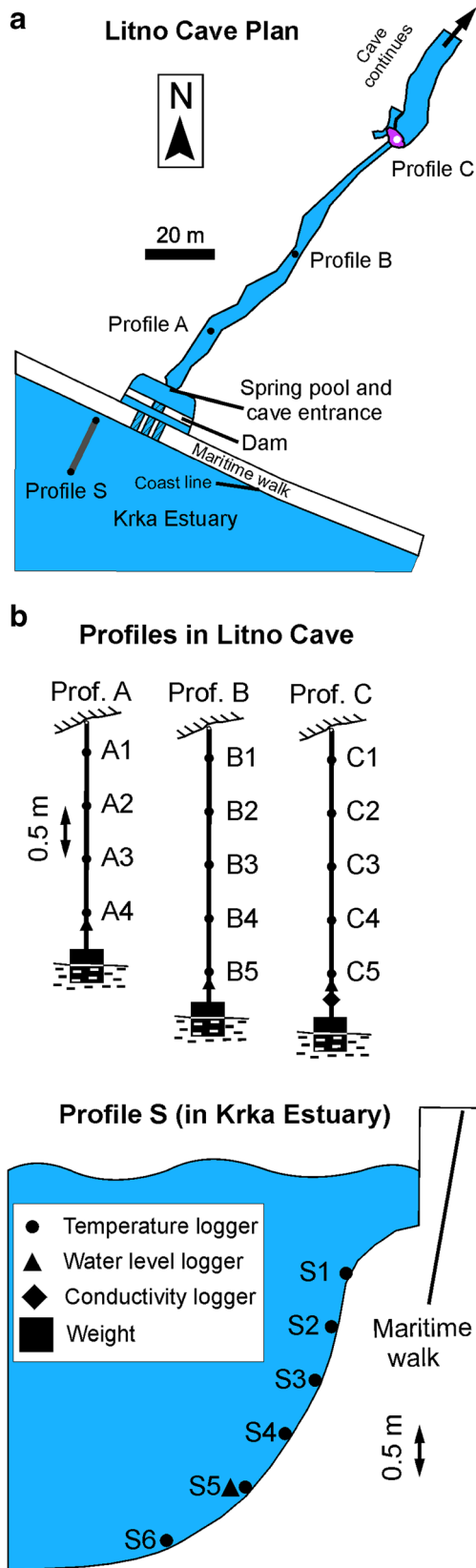

Fig. 1 Map of Krka Estuary region. The inset map provides a wider location within the Adriatic Sea of the selected area (black rectangle pointed with an arrow). The location of the submarine spring of Litno Cave is represented with a star symbol. Circles indicate the location of towns mentioned in the text as well as the city of Šibenik. Meteorological data for the period when this study was carried out are from Martinska Marine Research Station (square symbol)

a
Litno Cave Plan

b
Profiles in Litno Cave

Profile S (in Krka Estuary)

region in a terrain characterized by carbonate rocks predominantly folded and faulted parallel to the coast within a general

◀ **Fig. 2** Sketch showing the monitoring set up. **a** Plan view of the studied sector of Litno Cave (courtesy of Alan Kovačević and Tomislav Flajpan) with the location of the profiles where temperature was measured. The purple color in the cave plan indicates a small air pocket in the ceiling. **b** Sketch of the vertical profiles A, B and C, located inside Litno Cave. Temperature loggers within each profile were identified with the letter of the profile and an increasing number with depth. Sketch of the vertical profile located in Krka Estuary near the entrance of Litno Cave

Dinaric orientation (i.e., NW–SE). The bedrock where the cave is located consists of limestones from the Upper Cretaceous and Eocene epochs (Mamužić 1971; Brlek et al. 2014). The climate is Mediterranean with dry and hot summers and mild rainy winters (Filipčić 1998). At the meteorological station of Šibenik, the mean annual precipitation was 808 mm (period 1961–1990) with most precipitation from October to January whereas the mean annual temperature was 15.1 °C with mean minimum and maximum temperature in January (6.6 °C) and July (24.5 °C) respectively (Milković and Trninić 2007). The region is dominated by winds from N to NE (Bura/Bora), W (Maestral) and SW to SE (Jugo/Sirocco) with speeds that can exceed 30 m/s (Zaninović 2007; Vučetić and Bajić 2008). These winds enhance the mixing of the surface layer of Krka Estuary impacting the depth and gradient of the thermocline (Legović et al. 1991a). Krka Estuary is 23 km long, and upstream of the town of Skradin, the Adriatic Sea has little impact on Krka River (Fig. 1). Four kilometers upstream from Skradin, Krka River has several tufa cascades known as Skradinski Buk. The cascades impede the estuary to affect the river dynamics upstream from this site and Krka National Park has installed a monitoring station there to measure river discharge.

The coastline of Croatia is mostly composed of karst and has an extension of more than 6,000 km (Duplančić et al. 2004), whereby along this coast, hundreds of anchialine caves are cataloged (Surić et al. 2010). This study focuses on a particular anchialine cave called Litno, located north of an elongated bay of Krka Estuary oriented following major geological structures, nearby the town of Zaton (Fig. 1). The extension of Litno Cave is unknown since only some hundred metres have been explored. This research focuses along the 100 m of the cave closer to its entrance. The studied portion of the cave is a single sub-horizontal gallery oriented perpendicular to the coastline. The cave entrance and most of the cave is continuously submerged, although the whole system is very shallow and some large halls in the cave have small air pockets under the ceiling. The cave conduit is generally 2–4 m in diameter. The bottom of the cave has a bed of fine sediments that causes increased turbidity of the spring waters after strong currents.

In addition to Litno Cave being an anchialine cave, its entrance functions as a vrulja or submarine spring. The outflow of water from Litno is continuous through the year,

although the discharge varies seasonally. Litno is located in the proximity of the town of Zaton, and the municipality has installed a maritime walk just above sea level (i.e., <0.4 m) that passes in front of the cave entrance (Fig. 2). Additionally, a small concrete dam (<1 m in height) creates a pool that retains the spring water before entering the estuary. The continuous outflow of the spring to the pool is drained to the estuary through an opening in the centre of the dam and several tubes under the maritime walk (Fig. 2). No significant differences in water level were observed between the pool and the estuary during this survey. At the entrance of Litno Cave, the flow is always unidirectional (i.e., outflow). During spring tides and/or windy weather, the maritime walk can be partially flooded by the estuary; additionally, during the rainy season the discharge of Litno spring increases significantly and on occasions the water flows over the small dam and the maritime walk. Litno is the largest but not the only vrulja in Zaton Bay. In addition to these vruljas, diffuse discharge is observed during most of the year just at the base of the maritime walk and in the spring pool due to the rising up of groundwater.

Methods

Temperature was measured with TG-4100 loggers (Tinytag Aquatic 2) from Gemini Data Loggers that use thermistors that provide a precision of 0.001 °C and an accuracy of 0.5 °C. Water depth was measured with Sensus Ultra loggers from ReefNet that have 0.01 m resolution and 0.33-m accuracy. Conductivity was measured with a HOBO U24–002-C device from Onset that provided a precision of 0.01 μS/cm and an accuracy of 5%. The same device also measured temperature with precision of 0.01 °C and accuracy of 0.1 °C. Temperature in the latter device was only considered to evaluate the relationship of conductivity and temperature in the same spot and not to monitor the hydraulic dynamics of the system. Air temperature was measured with a HOBO U22–001 logger with resolution of 0.01 and accuracy of 0.21 °C. The device was set at ground level and hidden among rocks. This configuration provided shade, favored adequate ventilation and hid the device from tourists. Uncertainty associated with the precision and accuracy of all loggers should be considered as in the following example: an accuracy of 0.5 °C implies an uncertainty of ±0.25 °C.

The design of the network to characterize the system considered four vertical profiles with temperature loggers (Fig. 2). Three profiles were installed inside the cave and one in the estuary close by the cave entrance. The installation of tie points in the cave walls as well as the logger deployment and collection required scuba diving. Each profile in the cave consisted of 4 or 5 loggers knotted along a cord with a distance of 0.5 m between loggers. The cord was affixed to the cave

ceiling or walls with eye bolt anchors. At the lower end of the cord, a lead weight of 5 kg was used to keep the cord tense and guarantee the distance between loggers regardless of the current. The weights were partially buried in the bottom sediments of the cave. The knots of the temperature loggers prevent vertical displacements of these loggers; however, the loggers measuring water level were set to the cords by a ring bind limiting their free vertical displacement within 0.06 m. The sites where the profiles were installed were the most convenient locations considering the morphology of the cave. Of the profiles A, B and C, which were installed at 20, 55 and 100 m from the cave entrance respectively, profile A had the narrowest section and only four temperature loggers fit the cave section, while the other two profiles were wider and the loggers were set in the middle of their respective sections. The profile in the estuary required a different setting and the loggers were deployed at ground level following the slope of the estuary channel. A diving wrist depth gauge was used to deploy the consecutive loggers with a vertical distance of 0.5 m resulting in a profile extending for almost 20 m. Six loggers were set in this profile at depths from 1 to 3.5 m under water level, whereby the loggers were hidden among loose rocks, allowing water circulation and preventing tourists, divers and fishermen from finding them or accidentally misplacing them.

The time interval for all loggers was set to 5 min in order to have enough data to characterize water level variations related to tides and seiches that have frequencies <1 h (Orlić et al. 1991). The network of loggers was deployed in late September and collected 2 months later. This research focuses on the period from the 28th of September to 19th of October 2015, a period that captures the transitional dynamics in the system between the end of the dry season in summer and the onset of significant rains in autumn, representing the most dramatic hydrological change in the system during the annual cycle. Precipitation and wind data are from the meteorological station of the Marine Research Station of Martinska, only 6 km from the study site (Fig. 1), while the water level data of Krka River are from the Krka National Park database measured just upstream of the cascades of Skradinski Buk, 4 km east from the town of Skradin. Data to calculate discharge of the submarine spring were collected on the external side of the opening of the spring pool dam. A US Geological Survey Type AA current meter was used to measure water flow in at least 15 spots that were integrated according to the flooded section of the opening of the dam to calculate the discharge. The water level in the spring pool is affected by tides and a variable discharge during the day was expected (e.g., Menning et al. 2015). Additionally, small water jets springing up beyond the spring pool were observed; thus, the calculated discharge is only used as an approximate value of the real discharge from Litno Vrulja to provide the order of magnitude of the outflow discharge in the system. Relative water levels were calculated after normalizing the dataset to the average

value of the full time series. Spectral analyses and cross-correlation analyses were carried out with the software package PAST (Hammer and Harper 2006). Hydraulic head in the system was calculated from the difference between the normalized cave water level records and the estuary record after tidal oscillations were filtered out. The calculated hydraulic head has an uncertainty within 0.06 m, mostly related to the setting of the loggers along the cords in the cave. In order to evaluate which winds could affect the thermocline structure, winds with a persistent orientation were calculated. Winds were considered to have a persistent orientation when, during the previous 5 h, 2 standard deviations of the average hourly values were within 15°.

Results

Overview of the system

During the studied period, the surface air temperature was between 11 and 20 °C (Fig. 3). The amplitude of the thermal daily cycles was, for most days, between 2 and 4 °C with a mean daily temperature of 18.0 ± 1.5 °C; however, between the 10th and the 14th of November, the daily thermal cycles were diffuse and the mean daily temperatures were as low as 13.3 °C. The temperature of the water in the estuary in front of Litno Cave was generally warmer, oscillating between 16 and 24 °C. Daily thermal range in the estuary greatly varied depending on the depth, the weather conditions and the evolution of the thermocline. The impact of daily oscillations of the surface atmosphere temperature was observed only during some days of the first week, whereas other controls dominated the oscillations afterwards. During the first 2 weeks, mean daily temperature in the estuary was measured as 21.0 ± 1.5 °C; however, from the 10th of October a cooling trend was recorded starting with the loggers closer to the surface, reaching a mean daily temperature of 16.9 ± 0.7 °C by the end

of the studied period. The progressively cooler water temperature in the shallower loggers of the estuary is in agreement with the impact of the lower average temperature of the atmosphere on the surface of estuary waters (Fig. 3). Water temperature in the cave was always cooler than in the estuary, oscillating between 14.5 and 18.5 °C. Except for some loggers during the first week, the temperature was relatively stable around 16 ± 0.5 °C until the 11th of October, when a sudden drop in temperature of ~1 °C took place. After this cooling event, the temperature of all the loggers became nearly identical with 0.1 °C of maximum difference among loggers and a lack of high-frequency variability (e.g., thermal oscillations >0.1 °C within a day disappeared). During the first week of the survey, some cave loggers recorded up to 2.5 °C warmer temperature than others. These thermal deviations started and were more pronounced in deeper loggers of each profile (loggers A4, B5 and C5) affecting progressively to shallower loggers. These deviations also finished affecting the deeper loggers of each profile the last; however, these anomalies did not impact any of the shallower loggers of the three profiles.

Conductivity was measured in Litno Cave at the base of the profile located further away from the entrance: profile C (Fig. 2). During the first 2 weeks conductivity values greatly oscillated between 10 and 31 mS/cm (Fig. 4). On the 11th of October, conductivity values dropped suddenly (and reduced their variability) to 2.3 ± 0.2 mS/cm, while conductivity values decreased even more on October 15th reaching values of 0.5 ± 0.1 mS/cm. There is a clear relationship between conductivity and temperature values during the studied period (Fig. 4). Both parameters have a linear relationship and are highly correlated ($r^2 = 0.986$; p-value<0.001). The larger deviations between these parameters were limited to conductivity values exceeding 20 mS/cm.

After the field survey, previous observations that pointed towards the existence of unidirectional flow of water in the cave (i.e., outflow) were confirmed. A discharge of 45 L/s was calculated for the outflow of the spring pool on the 1st of

Fig. 3 Temperature records in the system. Water temperature records from the cave (red tones for site **a**, blue tones for site **b** and green tones for site **b**) and the estuary (gray tones) as well as the surface air temperature above the cave (black bold line). Different tones of colors within each profile indicate the depth, the darker records being deeper
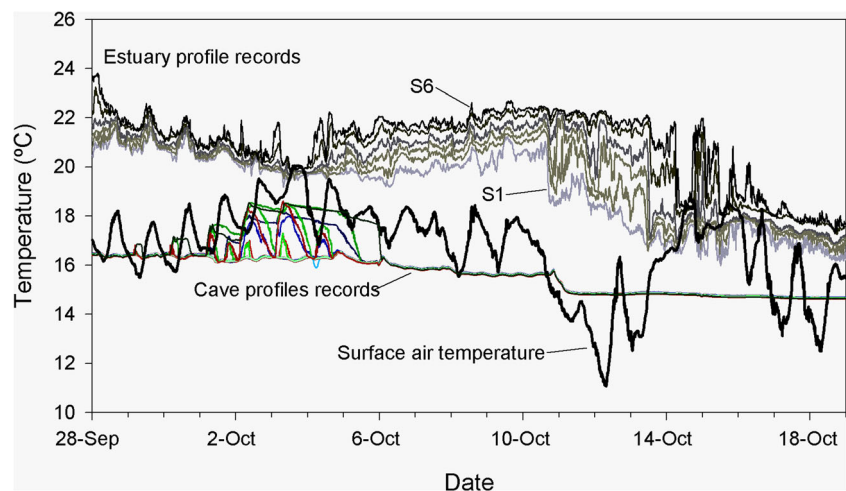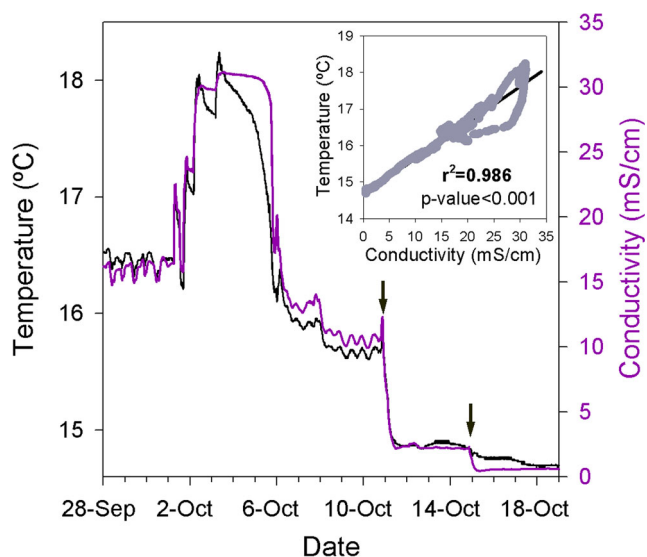
Fig. 4 Temperature and conductivity records from the bottom of profile C in Litno Cave. Vertical black arrows point to particular events of sudden drop of conductivity not related to tidal oscillations. The inset plot shows the correlation between both temperature and conductivity

October 2015 at 6:00 PM. At the time of measuring the discharge, diffuse discharge or other small vruljas were not observed around the submerged spring. Data to calculate the discharge were not measured again until the loggers were retrieved from the cave in late November, when the estimated discharge was 345 L/s (29th of November at 12:00 PM). At this time, the measured conductivity and temperature values (0.9 mS/cm and 14.6 °C) were in the same order of magnitude than during the period after the 11th of October 2015. In late November, several points of small concentrated discharge were observed beyond the spring pool and diffuse discharge along the coast at the base of the maritime walk; therefore, although most of the discharge around the studied system was still from Litno Vrulja, the real discharge of the groundwater from the system clearly exceeded the measured value.

Estuary profile

Tides in the studied sector of the estuary had typical maximum amplitudes of 0.4 m (Fig. 5). Spectral analyses on the relative sea level variability confirmed periods at the expected frequencies (i.e., around 12 and 24 h) together with another at 44 min (all of them significant with a 99% confidence interval). The latter oscillations were not recorded continuously and their amplitude is typically of 0.01–0.02 m. Seiches of similar frequency were already described in Krka Estuary (Orlić et al. 1991). Temperature was progressively warmer in the loggers located deeper along the profile. During the studied period the thermocline was always below or crossing the depths of the studied profile. The thickness and gradient of the thermocline varied significantly during the studied period providing different patterns of thermal profiles; thus, during the first days of record,

the thermocline was below the studied depths, providing a relative homogeneous thermal variability among loggers, with a narrow thermal range (i.e., <1 °C) and temperature responding to changes in surface air temperature. In these cases, the thermal gradients along the profile were typically 0.3–0.5 °C/m (e.g., 28th of September to 2nd of October and 18th–19th of October). Other patterns were also found, with occasional or continuous periods of increased thermal range (e.g., >2 °C). In some cases, the increase in temperature that caused larger thermal ranges, started progressively (in magnitude and time) with the deeper loggers at the time of rising tides and the situation reversed during the ebb tide. This pattern was found when the thermocline, located below or affecting the lower sector of the studied depths of the profile, was vertically displaced along with the tides (e.g., 3rd–5th and 14th–17th of October). In other cases, the thermal range among loggers was relatively large (i.e., around 2 °C or more) and was recorded continuously with limited impact of the tides. This pattern was recorded when the thermocline was within the studied depths (e.g., 6th–13th of October) and typical gradients during the studied period were 0.8 to 1. 6 °C/m. During the period of interest, the thermocline was never thin enough to be observed completely within the studied depths; however, a thermocline as thin as 1.5 m (with gradients around 2.5 °C/m) was recorded at the same site during other periods (Fig. 5). These results confirmed previous studies that concluded that Krka Estuary is well stratified (e.g., Legović et al. 1991a, b; Orlić et al. 1991).

Cave profiles

Vertical profiles A, B and C were located inside the cave at 20, 55 and 100 m from the entrance. The three profiles showed a very similar pattern, and besides the record of some loggers during the first week that had some significant changes, the thermal regime was very homogeneous (Fig. 6). The variability of relative water height in every profile was also measured. Although most of the cave is completely flooded, these loggers still recorded variations of the height of the water above them (i.e., variations in the phreatic level). Cross-correlation analysis indicates that the periodical water level variations inside the cave were synchronous to those recorded in the estuary, including the seiche frequency. These periodical water level variations had nearly the same amplitude during most of the record (Fig. 7). However, during some tidal cycles the three cave profiles recorded lower amplitude oscillations (up to 0.12 m) compared to those in the estuary. The most clear water-level differences were nonperiodical and were recorded during the 10th to 11th of October and 14th to 15th of October. Height of water level in the cave was up to 0.24 and 0.65 m higher than in the estuary during these two events. The thermal regime changed significantly after these two events. Prior to the events, small temperature oscillations were associated to tidal variations, whereas after the events thermal variability in the cave
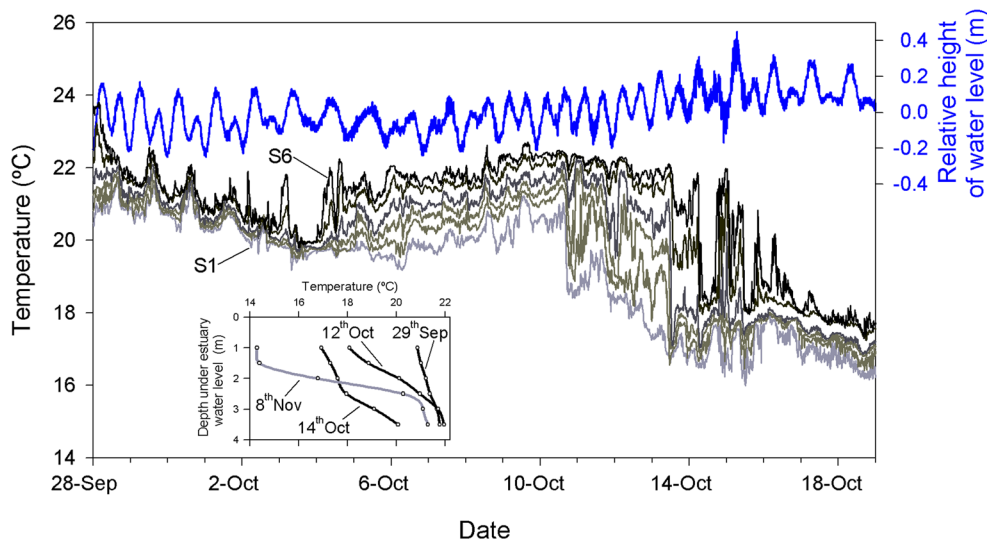
Fig. 5 Records of temperature and relative height of the water level in Krka Estuary (profile S). The different tones of gray show records measured at various depths along the profile; the darker tones correspond to loggers located deeper under the water level. The inset plot shows vertical profiles of temperature to illustrate the structure of the thermocline in selected days to help visualize the evolution of the temperature along the profile in the main figure. On the 29th of September, the thermocline was located below the studied section. On the 12th of October, the thermocline covered the studied section and, on the 14th of October, the thermocline covered the lower sector of the studied section. Additionally, to illustrate a clear example of a complete thermocline within the studied section, the figure shows the sharp thermocline (gray line) recorded beyond the period of focus in this study (8th of November)

was greatly reduced providing a very homogeneous record in all loggers without any relationship with tidal oscillations.

Previously it was reported that the temperature recorded in the cave profiles during the first week had substantial variability. During this period, the response of temperature to tidal oscillations is nonlinear. The thermal amplitude during some periods is <0.5 °C through the daily cycle and all loggers have proportional response. Before the significant precipitation events, the uppermost loggers of the three profiles always followed this pattern of variability. On the other hand, some loggers had a much larger response to the rise of water level in relation to tide oscillations, with thermal increases up to 2.2 °C. This thermal pattern implied a clear nonlinear relationship between water level variability and temperature. During the ebb tide the temperature of the loggers affected by these outstanding thermal increases returned to values (and variability) similar to other loggers of the profile. Exceptions occurred in the deeper loggers of profiles B and C. These loggers maintained higher temperatures than other loggers in their respective profiles, even during ebb tides. This pattern of relative high temperatures in the deeper loggers lasted several days in both profiles, being either completely independent of tidal oscillations or responding to the rise but not the drop of water level associated with tides. The periods with nonlinear response of temperature to tide oscillations always started and finished with the deeper logger of each profile. When several loggers of the same profile are affected by this nonlinear response of temperature to tide oscillations, the thermal anomalies are generally higher in the deeper loggers. The shallowest logger in profile C showed a drop of temperature

of almost 0.5 °C that was not observed in other logger of the series; this anomaly was recorded only on the 4th of October, lasted 3 h and had no obvious link to tidal oscillations.

Discussion

Evolution of the thermocline in the estuary

Krka Estuary has well-stratified waters with the halocline/thermocline generally within a depth range of 0.2–6.3 m and having a variable thickness of 0.1–3 m (Legović et al. 1991a). The thermocline in the estuary oscillated during the survey in phase with the tides, in agreement with previous studies in the region (Orlić et al. 1991; Mihanović et al. 2006). The thermocline was partially or completely below the studied depths of the estuary during some periods, while it was mostly or completely located within the studied depths of the estuary during others. The thermal gradient between loggers S6 and S1 was used, together with other environmental parameters (Fig. 8), to summarize the evolution of the thermocline shown in Fig. 5. At the start of the study, the thermocline descended to a depth below 3.5 m of the estuary level and progressively rose until the 4th of October. This trend was briefly interrupted by a drop of the thermocline below 3.5 m in this part of the bay caused by steady SE winds above 10 m/s (i.e., Jugo). After the persistent strong winds, the thermocline recovered the previous trend. From the 4th to 10th of October, the thermocline was at least partially above a depth of 3.5 m. During this period, the average gradient of the thermocline was ~0.8 °C/m. A series
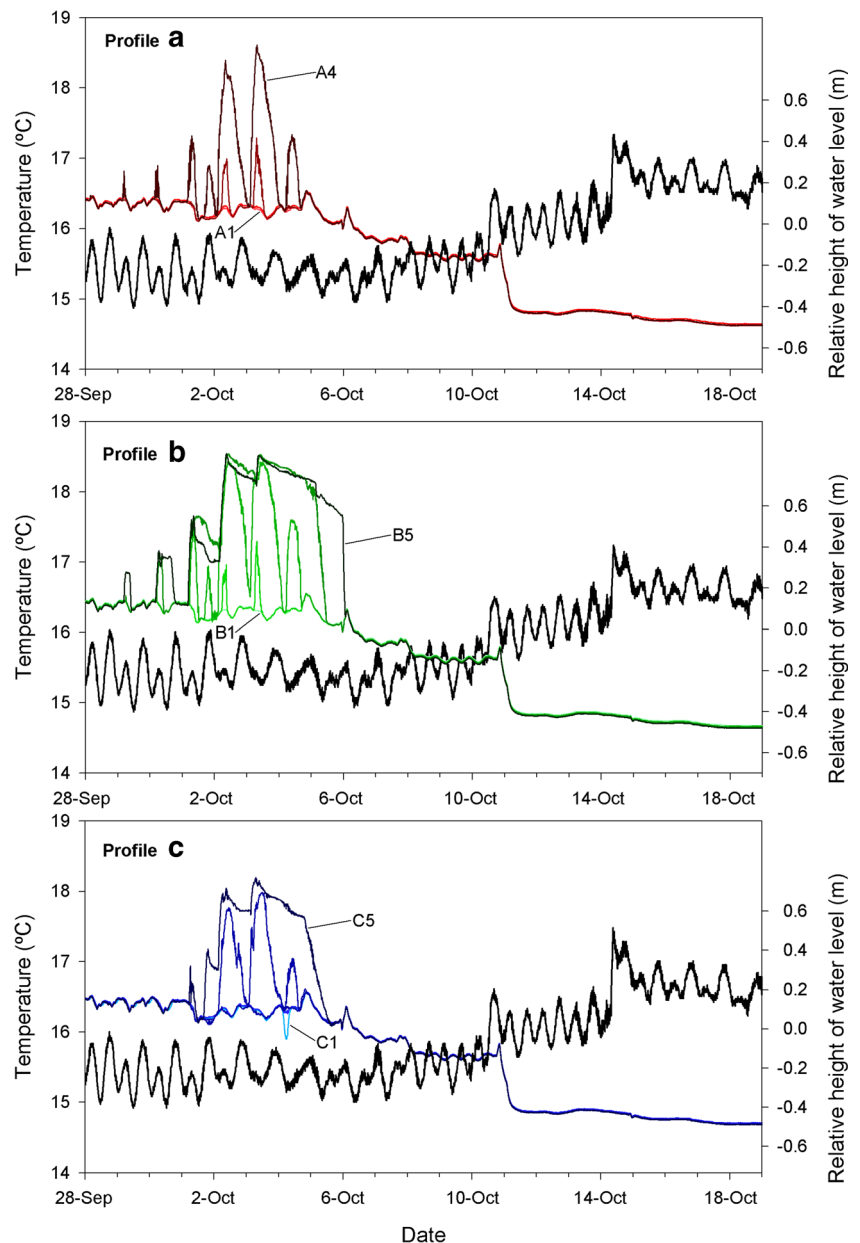
of small precipitation episodes took place between the 4th and 7th of October in the region. Martinska meteorological station recorded 21.2 mm of precipitation, although discharge of Krka River had a slightly earlier increase in water level, suggesting that these precipitation episodes were the result of local convective systems that occurred in the region. Thus, although they respond to the same synoptic situation they occurred at different times (within the duration of the synoptic situation) and likely with different intensity (Vučetić and Lončar 2008). On the evening of the 10th of October, a heavy precipitation event of 57.6 mm resulted in an enhanced stratification in the estuary waters; thus, the gradient of the thermocline increased to ~1.6 °C/m on average. The peak of discharge in Krka River had a delay of 1 day after this

precipitation event, and the river water level rose 0.4 m. During the days of 13th to 15th of October, persistent winds from the SE (i.e., Jugo) with average hourly speed between 15 and 25 m/s affected the region. The thermocline had a nonlinear response to this wind episode, although the strong winds occasionally forced the thermocline to be displaced to depths below 3.5 m. During this synoptic situation of Jugo wind, several precipitation episodes took place, the most important of them on the evening of the 14th of October, whereby during this event, 67.6 mm of precipitation were recorded at Martinska meteorological station. The peak of discharge in Krka River took place almost a day later and the river water level rose an additional 0.4 m. From the 15th of October onwards, the system recorded a progressive drop of the
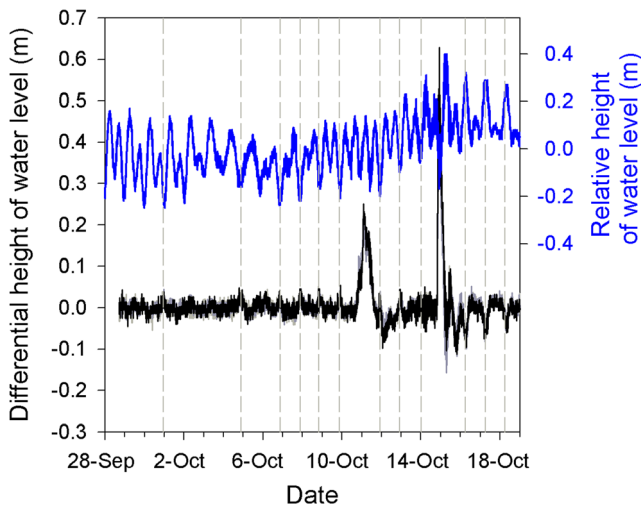
Fig. 7 Records of the differential height in water level between the cave profiles and the estuary within a day. Time series were normalized using the average value of the previous 24 h. The records of profile C–S (black line) profile B–S (dark gray line) and profile A–S (light gray line) are mostly superimposed over each other due to insignificant differences. The relative height of water level in the estuary (blue line) is shown to identify in-phase relationships of tidal oscillations in the estuary and water level variations in the cave. Vertical dashed lines of selected episodes of maximum and minimum elevation of the daily water level in the estuary are shown as reference. The cave records frequently show daily oscillations of water level higher than in the estuary during low tides but lower during high tides. These differences accounted for less than 0.06 m before the 10th of October

thermocline, and from the 17th to 19th of October, the thermocline was already below 3.5 m in depth. After the 15th of October, the thermal gradient above the thermocline was higher than during late September, which was the result of an increase in the thermal difference between loggers S4 and S5 located at depths of 2.5 and 3 m, respectively (Fig. 5). This is a local effect on the estuary influenced by the plume of fresh to brackish water that outflows from Litno Vrulja and was more intense after the precipitation events.

Evolution of the thermocline in the coastal aquifer

The profiles in the cave recorded temperature changes in phase with tidal oscillations similar to those recorded in the estuary. The nonlinear thermal response of the water temperature in the cave profiles clearly responds to changes in the thermocline in the aquifer (Fig. 6). The small thermal oscillations (<0.5 °C) recorded by most of the loggers associated with tide oscillations are related to the thermal gradient above the thermocline; however, during the first week, some loggers had a nonlinear thermal response to tidal oscillations. The magnitude of these thermal anomalies (up to 2.2 °C) and timing (coinciding with the rise of cave water level associated with tides) support that they represent a rise of the thermocline in the aquifer. The thermocline is recorded in the cave for the first time on the 29th of September and reaches its maximum height on the 3rd of October. This rising trend of the
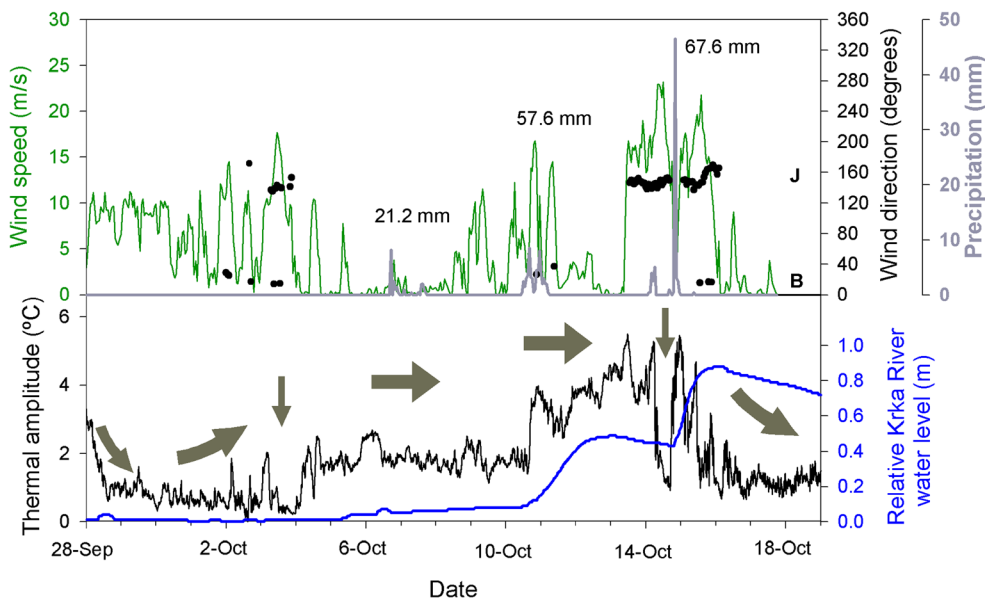

Fig. 8 Evolution of the thermocline in Krka Estuary around Litno Cave. Gray arrows indicate the trend of the thermocline being deeper (pointing down) or shallower (pointing up). Horizontal arrows indicate no major vertical displacements (ignoring tidal oscillations), whereas vertical arrows indicate temporary drops related to strong and persistent winds. **a** Data from Martinska meteorological station: wind speed (green line), precipitation (gray line) and persistent winds (black dots). The orientation of persistent winds suggests they were either Jugo (J) or Bura (B). **b** Thermal amplitude between loggers S6 and S1 (black line), illustrating the evolution of the thermocline. Relative water level of Krka River is from Skradinski Buk (blue line). The total amount of precipitation recorded during three different events around the 6th, 10th and 14th of October is reported

thermocline in the cave was also recorded in the estuary; however, while in the estuary, the thermocline stayed in a relatively steady position for 10 additional days, the thermocline in the aquifer started to drop on the 4th of October, and by the dawn of the 6th of October, the thermocline in the aquifer was already located below the cave. Therefore, although there were periods of synchronous oscillations of the thermocline in the cave and the estuary, it is obvious that the thermocline in the cave was affected by additional controls.

Litno Cave has a permanent outflow of water with a variable discharge. The daily water level oscillations were filtered to calculate the difference in water level between the cave and the estuary (Fig. 9). This analysis focuses on water level differences among loggers >0.06 m, that is the uncertainty related to the setting of the loggers. These calculations demonstrate that two events caused long-lasting differences of the water level in the aquifer compared to the estuary (Fig. 7); thus, the water level in the aquifer rose by >0.3 m above the estuary water level, increasing the hydraulic gradient and causing higher discharges. Changes in the hydraulic head started soon after the precipitation events and consequently are not related to the increase in discharge of Krka River that responded with 1 day of delay. The cave water level rose 0.15 m at its peak after the 57.6 mm precipitation event and up to 0.36 m after the 67.6 mm precipitation event. The conductivity of cave waters after these two events dropped below 3 mS/cm after the first precipitation event and below 0.6 mS/cm after the second event. The conductivity value recorded after the later precipitation event is already in agreement with conductivity values of fresh groundwater in carbonate aquifers of the region (e.g., Pavičić et al. 2006). These inputs of freshwater progressively diluted the brackish water of the aquifer and decreased its temperature. Although tides still affected the water level variability, there was no thermal gradient above the thermocline as before these events, and the temperature became homogeneous along the profiles; thus, the freshwater from the precipitation did not just pile up on top of the previous water mass. Instead, it displaced the brackish water to a depth beyond the cave bottom implying that this layer of water was thicker than 2 m, which is in agreement with the Ghyben-Herzberg approximation that, based on the expected density of these two water masses, suggests a downward displacement of the thermocline more than 40 times the increase of the hydraulic head (Michael et al. 2005; Fitts 2013). The thickness of this freshwater layer was much thicker than a simple even distribution of the infiltration along the aquifer, which supports horizontal flows of water in the aquifer towards Litno Cave, and explains the concentrated discharge in comparison with other diffuse discharge areas of the subterranean estuary. Additionally, the fast response of water level to precipitation supports a high hydraulic conductivity in this karst massif; thus, Litno Cave is the largest conduit among many others that are widespread in the karst of this coastal region. The high
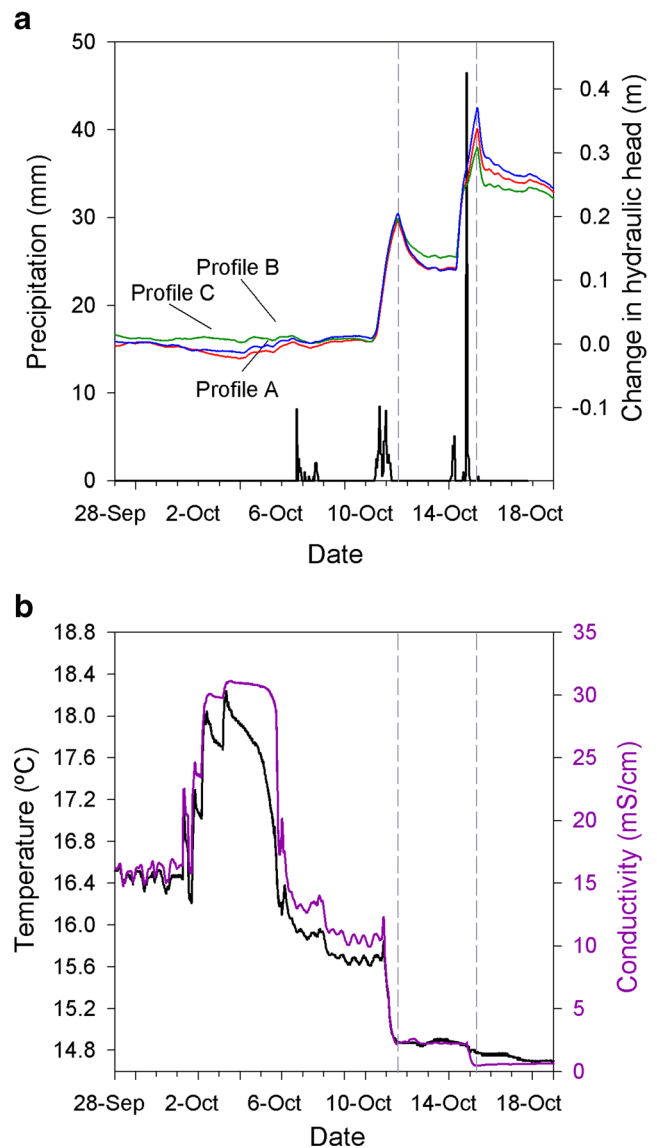

Fig. 9 Relative changes in hydraulic head of the coastal aquifer measured at profiles A, B and C compared to the water level of the estuary. **a** Comparison of hydraulic head and precipitation. A 24-h pass-band filter was applied to remove the tidal effects on water levels. Hydraulic head variations <0.06 m are within the uncertainty related to the setting of loggers. The precipitation record is from Martinska. Gray vertical dashed lines indicate the maximum water level in the aquifer. **b** Temperature and conductivity at the bottom of profile C. Gray vertical dashed lines are the same as in part **a**. Notice that the increase in the hydraulic head as well as the drop in conductivity and temperature are in response to the two large precipitation events

hydraulic conductivity explains why the tides in the estuary are in phase and do not have a reduced amplitude with distance to the estuary as in other systems (Robinson et al. 1998; Befus et al. 2013).

The response of the aquifer to precipitation events is nonlinear. The first precipitation event (i.e., the one with 21.2 mm of precipitation) had apparently less impact on the system than the two subsequent precipitation events. It was previously

discussed that episodes of convective precipitation probably had variable intensity and spatial distribution within some days. The cave did not record any sudden drop in temperature on the 6th of October at the time of this precipitation event being recorded in Martinska, as observed with other precipitation events; however, a drop of almost 0.5 °C was observed in logger C1 (the uppermost logger of this profile) on the 4th of October. This drop of temperature is not in phase with the tidal oscillations and occurred just before the thermocline in the cave started to drop, and the temporary cooling is considered to be the result of local convective storm providing precipitation in the peninsula between the towns of Zaton and Raslina at dawn on the 4th of October (Fig. 1). This hypothetical precipitation event caused a very well stratified layer of freshwater with a thickness < 0.5 m that only affected the upper logger of this profile. The thermal anomaly was not recorded in the upper loggers of A and B profiles. This circumstance could be caused by a short lasting and small discharge of freshwater supplied by a local vadose karst conduit near profile C. Such anomaly was likely not recorded in subsequent profiles along the flow of the cave due to the prompt thermal equilibration of the fresh and cave waters due to the large difference in discharge. The magnitude of the local precipitation event was likely lower than recorded in Martinska, although cannot be discarded as a nonlinear response of the aquifer to initial precipitation episodes after the summer. Unlike in the estuary, the drop of thermocline in the cave started on the 4th of October, just after this hypothetical precipitation event. At this time, together with the thermocline starting to drop, the cave recorded a progressive decrease in temperature > 0.5 °C in all loggers that lasted several days and was also associated with a dilution of the brackish waters (Fig. 9). All these data support the existence of a small local precipitation event around the 4th of October that impacted the dynamics of the coastal groundwater aquifer. The synoptic conditions that caused the precipitation in Martinska on the 6th and 7th of October were maintained from the 4th to the 8th of October, and the rise of water level on Krka River on the 5th supported that precipitation events took place during the 4th of October somewhere else in the basin. Therefore, all evidence supports that this precipitation event triggered a progressive change on the elevation of the thermocline in the coastal aquifer that lasted several days.

Hydrological dynamics in the coastal aquifer

The difference in timing, gradient and elevation of the thermocline in the three profiles of the cave also provided interesting information regarding the interaction of the estuary and the groundwater of the coastal aquifer. Profiles A, B and C were located at increasing distance from the cave entrance, and although loggers were vertically 0.5 m apart in each profile, the absolute elevation of the deeper logger of each profile differed

(Fig. 10). In the cave, the rise of the thermocline was detected first in profiles A and B but not in C on the 29th of September. The deepest temperature loggers from profiles A and C (A4 and C5) had almost a meter difference in elevation, the latter being deeper, suggesting a tilt towards land of the thermocline in relation to the phreatic level (i.e., ~1/35 m/m). At the same time, the thermocline in the estuary was below a depth of 3.5 m, supporting a tilt of the thermocline towards the estuary around the cave entrance (i.e., >1/25 m/m). Figure 10 illustrates the spatial relationship of the upper boundary of the thermocline during the high tide conditions of six different days that characterize the variety of situations recorded during the 3 weeks of this survey. The sketches in this figure show how the bulge of the upper boundary of the thermocline around profile A, that appeared on the 29th of September, was progressively flattened during subsequent days. This sinusoidal-like oscillation of the thermocline within the aquifer could have been caused as a result of a drop of the thermocline in the estuary during previous days. Thus, a significant vertical displacement of the estuary thermocline could have forced internal gravity waves affecting the position of the thermocline in the aquifer; however, as the cave recorded tidal oscillations in the aquifer, the frequency spectrum of the water level was complex.

The location of the thermocline in the coastal aquifer resulted from three controls: (1) the cave recorded the general trends of the thermocline in the estuary, although the synchronicity depended on the propagation of the internal gravity waves; (2) tidal oscillations within the cave displaced the thermocline vertically; (3) the third control was the hydraulic head of the aquifer resulting from the infiltration of precipitation. The increased hydraulic head was the result of a new layer of freshwater piling up on top of previous water masses of the aquifer. The latter control caused much larger displacements of the thermocline than the other two controls. The recharge of coastal aquifers during the rain season generally displaces the thermocline deeper in the aquifer and offshore (Michael et al. 2005; Menning et al. 2015). The discharge of Krka River in the estuary also has a positive correlation with the depth of thermocline (Legović et al. 1991b); therefore, regional precipitation is expected to impact the cave thermocline by the increase of the freshwater recharge in the aquifer or by the increase in river discharge in case of lack of precipitation in the recharge area of the aquifer. The impact of tides on the depth of the thermocline for a particular location is limited by the amplitude of the tides; thus, tides become a major control on the cave water temperature only when the thermocline is already in the proximity of the studied elevation.

The temperature pattern of the cave loggers showed a very distinct structure before and after the onset of the second precipitation event. The increase in hydraulic head and the drastic reduction of conductivity supports that freshwater entered the aquifer. The thermal signal of all these loggers was very homogeneous, unlike the thermal regime recorded before the
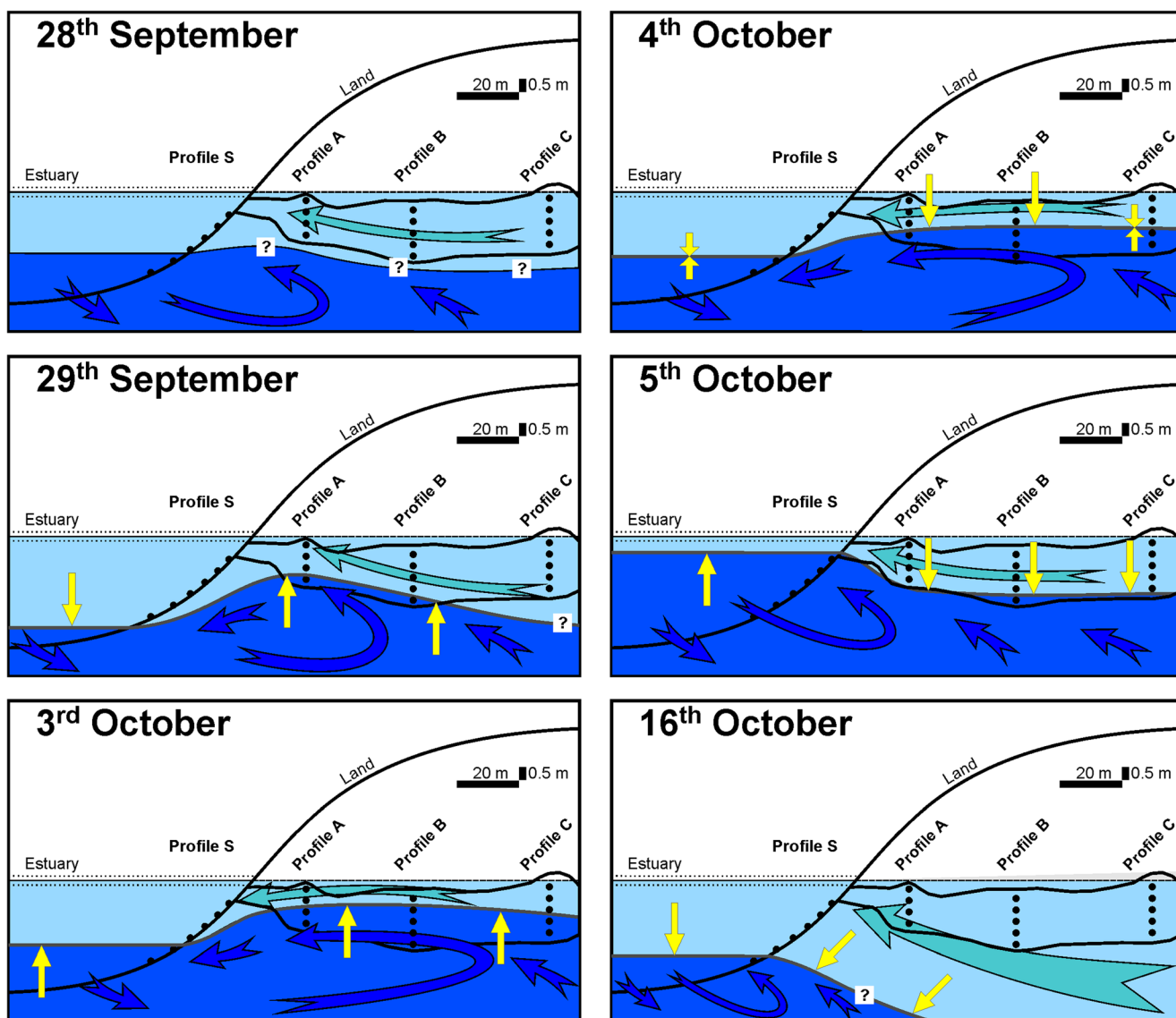
Fig. 10 Sketches showing the evolution of the coastal aquifer during high tide conditions for a series of selected days. Dots represent the location of the temperature loggers in profiles A, B, C and S. Maximum tidal oscillation in the estuary is also provided (dotted lines). The layer of fresh to brackish water is in pale blue and the layer of brackish water to seawater under the upper boundary of the thermocline is in dark blue. Dark and pale blue arrows indicate the direction of the flow in each layer. Yellow arrows show the trend of the thermocline in the estuary or a certain sector of the aquifer after the previous sketch

recharge events. During the first 2 weeks, tidal oscillations caused high-frequency thermal variability resulting from the thermal gradient either on top of the thermocline or within the thermocline. The conductivity values were typical of brackish water above the thermocline (i.e., 10–15 mS/cm) and of saline water below the thermocline upper boundary (i.e., >30 mS/cm). The discharge from Litno Cave on the 1st of October was 45 L/s, a relatively high value for a spring at the end of the dry season considering the limited drainage area of the peninsula where Litno Cave is located (Fig. 1). The source of this water is from the uppermost part of the water column of the estuary, which explains the brackish nature of this water. Tides in the cave and the estuary are synchronous, although their amplitude differed as much as 0.06 m (Fig. 7) until the 10th to 11th of October, when the second precipitation event took place; therefore, during the high tides before the second precipitation event, a hydraulic gradient towards the aquifer enabled the estuary water to flow towards the aquifer. Since there is no evidence of reverse flow in Litno spring, likely the inflow of estuarine water to the aquifer occurred along the coast between Prokljan Lake and the cave; thus, the relative lower hydraulic head in the aquifer compared to the estuary during the high tides before the 10th to 11th of October (Fig. 9), favored the intermittent flooding of the aquifer by estuarine water. Thus, at the end of the dry season, the outflow from Litno Cave resulted mostly of water from the estuary re-circulated through the karst

aquifer; however, on the other hand, after precipitation events partially recharged the karst aquifer, the freshwater layer pushed down the brackish and saline water masses of the subterranean estuary. Since the recharge produced a hydraulic head in the aquifer, this gravitational barrier prevented the flow of water from the estuary to the aquifer.

Conclusions

Temperature was used, supported by conductivity and water level measurements, to survey the hydrological dynamics of a complex coastal karst aquifer in Krka Estuary (Croatia). During the studied period, temperature was highly correlated with conductivity and was a good indicator of the interaction of fresh, brackish and saline water masses. In the studied case, temperature was found to be a powerful tool to capture the general dynamics of the coastal aquifer and to identify the controls that dominate the evolution of the thermocline: (1) the recharge of freshwater via infiltration of precipitation, (2) the evolution of the thermocline in the estuary and (3) the tidal oscillations. This complex system is characterized by three water masses—the brackish and saline water masses of the well stratified Krka Estuary and the freshwater of the precipitation infiltrated into the aquifer. The distinct thermal variability of each water mass during the studied period and a specifically designed network of loggers were sufficient to use temperature as a tracer of the hydrological dynamics of this complex system. The source of water that outflows by this submarine spring depends on the evolution of the saline intrusion. During the studied period, the precipitation over the region fed the aquifer with freshwater, which displaced brackish groundwater towards deeper and offshore positions. However, at the end of the dry season, in summer, the reduction of the fresh groundwater body caused the saline intrusion to be located in shallow and inland positions. In addition, the existence of a hydraulic gradient towards the aquifer during high tides, caused occasional inflow of water from Krka Estuary to the aquifer. At the end of the dry season, the source of the Litno Cave outflow was the brackish water over the thermocline in the estuary. Occasionally, saline water below the thermocline also flew by the submerged cave, contributing to the water outflow of the submarine spring. After the onset of significant precipitation events that recharged the aquifer, the saline intrusion was displaced, the discharge of the spring increased significantly, and the source of water flowing out of the submarine spring was restricted to freshwater resulting from the infiltration of precipitation.

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