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Hydrology of Two Coastal Karst Cryptodepressions in Croatia: Vrana Lake *vs* Vrana Lake

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ABSTRACT

This paper compares hydrological systems of two coastal karst cryptodepressions which represent the two largest lakes in Croatia, and are known by the same name of Vrana Lake. The paper analyzes Vrana Lake in Dalmatia (surface 30 km²; lowest point at –3.0 msl; occasional records of increased salinity with chloride content up to 4500 mg/L), and Vrana Lake on island Cres (surface 5,75 km²; lowest point at –61.3 msl; and constant salinity values with chloride content of about 100 mg/L). Both lakes represent valuable water resources on a water-poor karst area and have a status of protected localities – Vrana lake in Dalmatia as a nature park, and Vrana lake on Cres (the only source of island's drinking water) as a strict zone of sanitary protection. The lakes have different hydrological, limnological and ecological characteristics, which are compared in this work for the first time.

The aim of this work was to assess the hydrological stability of the lake systems, define their relation with karstic aquifer and the sea and determine the risks of undesirable changes (salification due to present anthropogenic influence and global climate changes), all based on simple analysis of basic lake systems' dynamics.

The area of study is hydrology of coastal karst systems, with an emphasis on limnological research. The methods used are simple stochastic analysis of data time series, appropriate for modest background resources available – continuous data on sea and lake water level oscillations, and results from occasional monitorings of water conductivity and salinity. Attained results are interpreted in the context of Ghyben-Herzberg rule on freshwater – saltwater equilibrium.

Results of conducted analysis showed different sensitivity of analyzed lakes towards hydrological conditions, and demonstrated different trends during the same observed period (1948-2005). Vrana Lake on the island Cres, whose water level oscillations range between 9.11 – 15.93 msl, demonstrated a siginficant trend of decrement in minimum annual water level values (0.41 % / year), while Vrana Lake in Dalmatia, with water level oscillations ranging between 0.03 – 2.24 msl, demonstrated a trend of increment in minimum annual water level values of 1.28 % / year.

It is concluded that different trends can be related to local anthropogenic influence (water usage from the lake and its catchment), but also to global climate changes which show significant influence on this fragile hydrological systems, even in this short-term analyzed period.

Keywords: karst lakes, water level oscillation dynamics, water management, anthropogenic risks, salification

INTRODUCTION

This paper analyzes two coastal lakes from the karst area on the eastern coast of the Adriatic sea, both known by the same name of Vrana Lake. These two largest lakes in Croatia, one of which is located in the coastal part of Dalmatia, and the other on the island Cres (Figure 1), present cryptodepressions which interact differently with the sea and the groundwaters that feed them, due to their position in the vicinity of the sea and the specifities of their karstic aquifers. Being valuable water resources in an otherwise water-poor karst area, both lakes deserved a status of protected locality – Vrana Lake in Dalmatia as a nature park, and Vrana Lake on the island Cres, the only source of island's drinking water, as the most strict zone of sanitary protection. The lakes are dynamic systems, in which untill now detected changes of state are not exclusively related to historical circumstances that have changed on a level of geological periods, but can also be expected in the future. The idea of this work was to compare for the first time seemingly incomparable hydrological systems of these two lakes, situated in the same regional area.

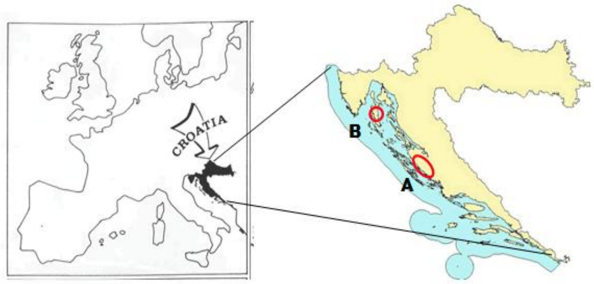

Figure 1. Position of the analyzed lakes in the coastal area of Croatia (a) Vrana Lake in Dalmatia, (B) Vrana Lake on the island Cres

Most attention was given to hydrological characteristics of the lakes, which best determine the stability of the lake systems and their relation to the sea. Anthropogenic influences were also analyzed, as they can not only induce small successive changes, but also cause significant shifts in ecological conditions, subsequently changing biological characteristics of these fragile ecosystems, and even threatening the very existence of the lake systems. Most comprehensive changes can be expected in the case of undermining the freshwater – saltwater equilibrium, due to global changes of sea level intensified in the last 20 years, but also strongly influenced by anthropogenic factors. Among risks caused by human activities, this paper only deals with inappropriate regime and quantity of water usage, and structural interventions in lake systems. Risks related to excessive pollutants inflow into the systems, although present and especially significant for Vrana Lake in Dalmatia, have not been analyzed in this work due to complexity of the subject topic.

Important to note is that data used in this work, except for hydrological data on water level oscillations, salinity and conductivity, are not related to any systematic monitoring of lake – aquifer – sea relationship, which has never been conducted as such in the analyzed locations. Other data have mostly been collected during short-term investigations directed towards possibility of using water from the lake or its aquifer for water supply (Vrana Lake on Cres) or towards planning structural interventions for the purpose of melioration (Vrana Lake in Dalmatia). Consequently, available data are partial, heterogenous and scarce. But even as such are indicative of the risk of undesirable successions, and strongly imply the need of paying attention to these lake systems apart from the common exclusive concept of water usage possibilities, to be able to protect them from potential negative changes. This especially applies for Vrana Lake in Dalmatia which lacks even the detailed geodetic survey to attain data on the total lake's volume (of the order of magnitude between $50x10^6$ and $100x10^6$ m^3).

It should also be noted that data on salinity during some periods were monitored by different water quality parameters: conductivity (μS/cm) and content of chloride (mg/L) being the most abundant salt in the water. This makes them only relatively comparable, in relation to the maximums approved for drinking water: 2500 μS/cm for conductivity and 250 mg/L for chloride according to Croatian legislatives. In some periods though, both parameters were monitored.

Basic Characteristics of Analyzed Water Systems

Vrana Lake in Dalmatia

Vrana Lake in Dalmatia is the largest natural lake in Croatia by surface (30 km^2). With the length of 13.6 km and width of 1.4 – 3.5 km it lays in the immediate hinterland of middle-dalmatian coastal area, from where it is being fed by surface waterflows and a number of springs. (Figure 2). It is a young water phenomenon, formation of which has begun about 9.000 years back in time, when the sea level is calculated to have been much lower than today (Fritz 1984). Lake's water level oscillates in a narrow range between 0.03 meters above sea level (msl) in year 1990 and 2.24 msl in years 1974 and 1994, with the lowest point of the lake being only 3.0 meters below sea level. It is divided from the sea by a narrow (0.8 - 2.5 km) karst ridge, through which the lake communicates with the sea.

Due to its natural values and extraordinary biological diversity, in 1999 Vrana lake was proclaimed a nature park, together with its surrounding area covering 57 km^2 in total (Figure 3). The wetland area comprising reedbeds and floodplains at the northwest of the lake represents the last remain of what used to be the vast Mud of Vrana, a marsh that had covered the entire Vrana field and served as habitat for numerous endangered species, especially of waterfowl. Because of its importance for ornithofauna this nortwestern part of the Nature park is specially protected by the status of the Ornithological Reserve (with the area of 8.65 km^2). The former Mud of Vrana was dried out through the Prosika canal, which was dug through in 1770 to attain new agricultural areas in Vrana field and protect them from seasonal floodings. The 800 m long canal has been broadened and deepened several times, and in 1948 it gained its final dimensions: 8 m of width and the lowest point at about 0.35 msl (Katalinić 2007). During water periods the lake water exits into the sea, but in the dry periods it can level with sea water. In extremely dry periods, when abundant evaporation causes the lake level to drop beneath the sea level, Prosika canal allows entrance of sea water into the lake.

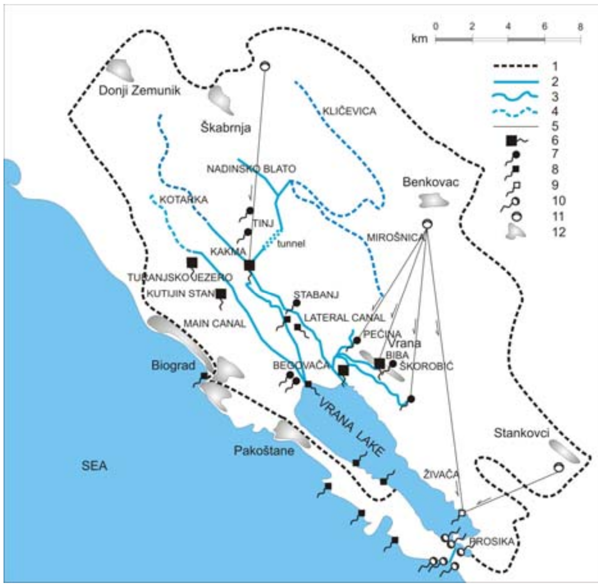

Figure 2 – Schematic overview of Vrana Lake in Dalmatia catchment area.
Legend: (1) hydrogeological catchment boundary, (2) regulation canal, (3) permanent natural watercourse, (4) intermittent natural watercourse, (5) undergound hydrogeological connection (6) water intake for water supply, (7) affluent natural spring, (8) brackish spring, (9) vrulja, (10) estavelle, (11) ponor, (12) settlement

Namely, according to Berakovic (1983), evaporation from water surface amounts about 1660 mm/year, and average yearly deficit with respect to annual precipitation amounts up to 730 mm, which means up to $22x10^6$ m^3 in dry years. More recent data according to Svonja (2003) supply us with slightly lower values (evaporation 1403 mm, average yearly deficit 483 mm, that is $14.5x10^6$ m^3), but this does not change the fact that part of the water balance in dry periods is being supplemented by intrusions of salt underground water and even sea water itself into the lake.

According to Fritz (1984) and Kapelj et al (2003) Vrana Lake's catchment area is about 470 km^2 large, with average annual precipitation of about 1000 mm (Berakovic 1983), and average air temperatures of 13.8 ^{0}C. Water temperature varies from short-term freezing processes at the marginal parts of lake, to about 30 ^{0}C. The catchment is formed mostly by carbonate limestone structures. A smaller part of the catchment consists of partly permeable dolomite rocks, and also impermeable clastic sediments of eocene Flysch, directing the underground waterflows. Bottom of the lake is formed by quaternary lake sediments with maximum determined thickness of 29 m. Main inflows enter the lake through a network of built melioration canals (Main Canal, Lateral Canal), which accept waters from periodical watercourses (Kotarka, Mirosnica, Klicevica) and permanent watercourse Škorobić. Underground waters of the catchment rise through a number of springs, the most significant regarding the minimum affluency (Kapelj et al 2003) being Kakma (0.080 m^3s^{-1}), Biba (0.015 m^3s^{-1}), Begovaca (0.005 m^3s^{-1}), Veliki Stabanj and Mali Stabanj, Pecina and others. Water intake in the karstic aquifer Turanjsko jezero (0.070 m^3s^{-1}) has been made, as well as the drilled well Kutijin stan (0.036 m^3s^{-1}). Based on water level oscillation balance calculations (Beraković 1983), total balance of average annual inflow into Vrana Lake amounts 2.48 m^3s^{-1} for the period from 1963 to 1980, oscillating on the level of average monthly values from 0.089 m^3s^{-1} during on average driest July to 4.64 m^3s^{-1} during on average most rainy January. Svonja (2003) estimates considerably higher values (4.2 m^3s^{-1}) of average annual inflows, based on analysis of potential inflows from the catchment itself.

Some flows and springs in the catchment are engaged in water supply and melioration. According to attainable data, annual pumping estimates amount $1.9x10^6$ m^3 for water supply and about $1.0x10^6$ m^3 for melioration, which represents a relatively small portion (3 – 4%) of the above mentioned total average annual inflow balance. But, during dry periods melioration and water supply spend about 0.200 m^3s^{-1}, which doubles the average freshwater inflow estimated for these periods. Taking into notion former big plans for melioration development with estimated annual needs of up to $13x10^6$ m^3 (Rozić 1994), which are currently being noted, it becomes obvious that balance relations in the lake could be seriously disturbed during the dry periods, even with the slightest increase of water usage from canals and springs filling the lake.

Due to decreased inflows following water usage, as well as evaporation deficits, salinity of Vrana Lake's water varies significantly throughout the year, especially in the extremely dry years when sea level exceeds water level of the lake. Data collected in continuous monitoring of lake's salinity at location II (Figure 3) in the period 1988-1992 (Romic and Tomic 1997) show variations in conductivity between 2800 and 14500 μS/cm, with an average of 6690 μS/cm. Chloride values, representing in the form of natrium chloride more than 90% of all salts, ranged in certain years (1988 and 1990) from about 750 - 1500 mg/L , rising in 1990 up to more than 4500 mg/L, and varying during 1991 and 1992 between about 1500 – 3000 mg/L. Therefore, during the monitored period, water salinity multipled by a factor of six, and in only one year (1990) it more than tripled. According to research conducted in 1995 (IGI 1995), chloride content of

Vrana Lake's water ranged from 235 mg/L (in March – during the rainy part of the year) and 960 mg/L (in July and August – during the dry part of the year), varying the average portion of sea water between 1% and 5%. The samplings were made at a depth of 1 meter below surface. Due to small depth of lake and strong surface currents caused by wind and waves, the lake does not show seasonal thermal stratification nor change of salinity with depth, except for mild changes in the deepest part of the lake.

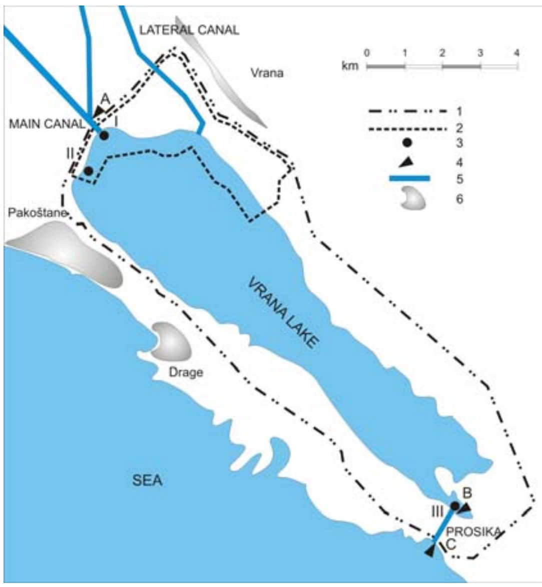

Figure 3. Vrana Lake in Dalmatia with an overview of observed locations
Legend: (1) Nature Park boundary, (2) Ornithological Reserve boundary, (3) water quality sampling point, (4) hydrological station, (5) regulation canal, (6) settlement

Available results of water quality monitoring, conducted with frequency of up to 12 times a year since 1982, show that in a longer time period chloride content also tends to retain higher values, droping however, at short intervals, to significantly lower values, which can be explained by local conditions – irregular increased inflows of fresh water. Starting from 2000, conductivity and chloride content are being measured monthly at three locations in Vrana Lake – Dalmatia: location I at the northwestern part of the lake, situtated directly at the estuary of Main canal bringing water from the Vrana field into the lake; location II also at the nortwestern part of the lake, close to the camping site Crkvine and away from any visible or permanent inflows of surface or undergound water; and location III at the southeastern part of the lake next to Prosika canal. Relation between water level oscillations and conductivity oscillations at described locations is given in Figure 4, and it clearly demonstrates a cyclic exchange of water level and conductivity oscillations, as a result of increased inflow of chloride during low water level situations. It also shows opposite trends during the analyzed six years period: water level decrease trend and conductivity (and chloride) increase trend, at all three localities. Given figure points out better coinciding in conductivity oscillations between locations II and III, while data from location I show higher conductivity values in situations that are not followed by similar events on the other two localities. This anomaly can be related to anthropogenic influences – increased intake of salt through the regulation canals, as a result of fertilizing and washing out of the surrounding agricultural area.

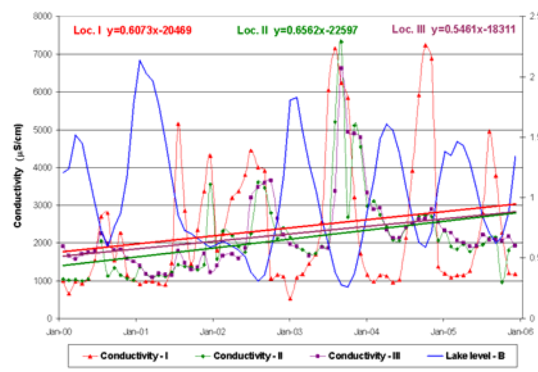

Figure 4. Comparative overview of average monthly .water level oscillations in Vrana Lake in Dalmatia and results of conductivity monitoring at three locations in the lake

Comparison of characteristic indicators (average, maximum and minimum values) in monitoring air temperature, water temperature, conductivity and chloride is given in the Table 1. The table shows highest average conductivity at location I, but highest chloride content at location II, both on the opposite side of Prosika canal. It is obvious that the salification mechanisms include underground saltwater intrusions through the permeable karstic aquifer. Minimum recorded chloride contents at location I are indicative of the direct influence of surface water on this location, resulting in irregular minimum chloride content water inflows.

Table 1. Overview of characteristic parameters of water quality monitoring at Vrana Lake in Dalmatia (2000-2005)

Location	Air temperature (^{0}C)	Water temperature (^{0}C)	Conductivity (□S/cm)	Chloride (mg/L)
Average values				
I	*17.8*	*16.1*	*2376.6*	*605.4*
II	*17.3*	*16.6*	*2096.6*	*709.2*
III	*16.5*	*16.2*	*2238.8*	*608.4*
Maximum recorded values				
I	*32.0*	*29.4*	*7240.0*	*2750.0*
II	*29.0*	*29.3*	*7330.0*	*3200.0*
III	*29.0*	*30.4*	*6620.0*	*3250.0*
Minimum recorded values				
I	*1.0*	*2.3*	*532.0*	*28.0*
II	*2.0*	*1.9*	*958.0*	*250.0*
III	*2.0*	*1.2*	*1087.0*	*144.0*
Number of samples				
I	*34*	*71*	*72*	*72*
II	*32*	*71*	*72*	*71*
III	*31*	*70*	*69*	*69*

Regarding the scope of salification processes, ideas of outflow control in the form of a barrier at Prosika canal have been formed, and also, linked to the former plans for melioration from Vrana Lake, ideas of building a damn to compartmentalize the upstream part of the lake have long existed, aiming to increase the lake's water level and prevent sea water from entering into the lake and its aquifer during the dry periods. Plans for melioration from Vrana Lake have been discarded, but it is now proved that even existing water usage from the lake and its aquifer endangers the stability of lake system and its organisms, and ensuring an ecologically acceptable waterflow in the system feeding the lake is a must (Misetic and Mrakovcic 2003, Mrakovcic et al 2003).

Vrana Lake on The Island Cres

Differing from the above described, much more shallow and in geological terms significantly younger Vrana Lake in Dalmatia, Vrana Lake on the island Cres (Figure 5) had been formed in early Pleistocene and had exchanged several lake-land phases through former geological history (Biondic et al 1996). These phases were determined by global shifts in sea level and related changes in karstification and draining of the area. With the average surface of about 5.75 km^2, and volume of up to 220x10^6 m^3, the lake represents not only the most significant water phenomenon in the islands of the Adriatic Sea, but also in the whole Mediterranean.

Average annual precipitation amounts 1064 mm, approximating the average evaporation from the water surface of 1161 mm (Ozanić and Rubinic 2001). The lake is a cryptodepression with the lowest point recorded in a funnel depression at even 61.3 m below sea level. The island Cres is a very narrow island, elongated in shape, with the surface of 405.78 km^2 and with the biggest width of 10 km in the middle part of the island where Vrana Lake is situated. It is formed mainly by karstic carbonate rocks from Cretaceous, with dolomites dominating over limestone (Biondic et al 1995).

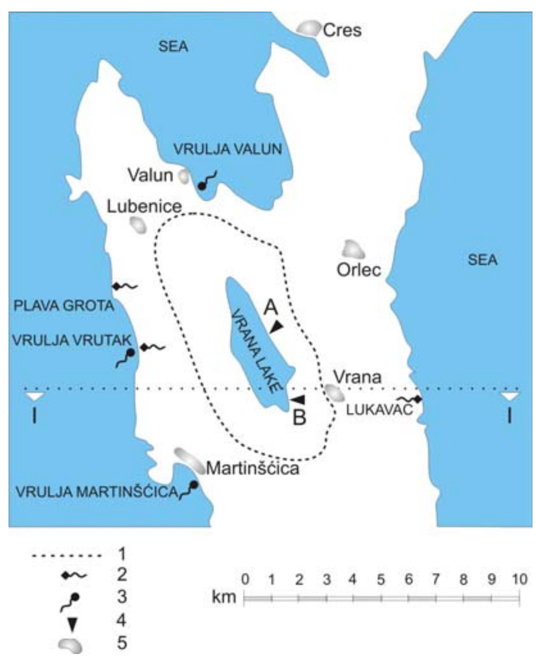

Figure 5. Position of Vrana Lake and its catchment on the island Cres Legend: (1) orographic cattchment boundary (2) coastal brackish spring, (3) vrulja, (4) hydrological station, (5) settlement

The lake has no visible surface inflows (apart from scarce flooding phenomenons) nor springs, and the entire mechanism of water inflow and outflow is based on unlocalized underground routes. In the coastal area of Cres, covering broader surroundings of Vrana Lake, a number of coastal springs and vruljas have been recorded. Although the lake is only 3 – 5 km distant from the sea, it represents an extraordinary freshwater phenomenon on an otherwise water-poor island Cres (|Figures 5 and 6), maintaining the equilibrium between fresh and salt water on principles of Ghyben-Herzberg hydrostatic rule, which can be applied, paying attention to certain limitations, to karstic aquifers as well (Bonacci 1987).

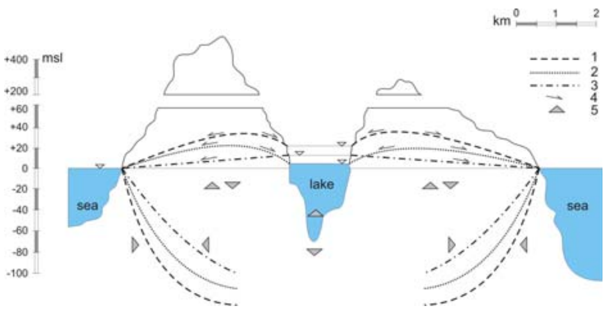

Figure 6. Profile section I-I (in Figure 5) of Vrana Lake on Cres, with a scheme of freshwater – saltwater equilibrium in characteristic hydrological states Legend: (1) hydrological conditions during high lake water level, (2) hydrological conditions during lower lake water level (3) hydrological conditions during dry periods, (4) gradients of underground flows, (5) general underground water flowing directions and freshwater – saltwater borderline shifts

Besides being the only source for water supply of the islands Cres and Lošinj, the lake possesses an additional ecological significance as the only stagnant freshwater body of the island Cres, thus presenting a specific ecosystem, separated by sea from other freshwater systems. Although former investigations of biological characteristics the lake have been directed mainly towards defining its trophic state, it would be interested to open the questions of the origin of organisms inhabiting this isolated ecosystem.

The lake is characterized by large oscillations of water levels – between 9.11 msl (in 1990) and 15.93 msl (in 1961), with the average level of about 13 msl. Yearly pumping for water supply amounts up to 2.3×10^6 m^3 of excellent quality water (which gives an average of 72 L/s), and in periods of maximum water requirements average daily pumping can rise up to 160 l/s. This represents annual pumping of about 12 - 13% of average annual inflow, while in the dry periods, when the needs for water are greatest, average monthly pumping (0.120 m^3s^{-1}) can reach about 50% of average monthly inflow.

Since the beginning of pumping in 1952 till today, 65 $\times 10^6$ m^3 of water have been pumped out of the lake, which would give 11.3 m of water gauge considering the average level of the lake. But, according to the results of a mathematical simulation model, it has been determined that the lake level has decreased for 2.2 m due to pumping, while the rest of the pumped out water has been supplemented by decrease in sinking water deficits and increase in filling of the lake from the surrounding karstic aquifer. This is explained by the vertical gradient of function of deficits, which means that lower levels of lake water are followed by a decrease in water losses from the lake and relative increase in inflows as well. Average inflows into the lake amount 0.588 m^3s^{-1}, and average sinking deficits about 0.393 m^3s^{-1} (Ozanić and Rubinic 2001). This facts, along with other water balance indicators, according to the used mathematical hydrological model, indicate the retainment of water in the lake for 32 years. Almost identical result, therefore confirming the accuracy of the used hydrological model, was gained in the independent research of water isotope composition (^2H,^3H,^{18}O, ^{13}C), which gave average water retainment estimates between 30 and 40 years (Hertelendi et al 1995)

Figure 6 shows a schematic overview of characteristic states of the dynamic relation between water levels of the sea, the lake and the undergound. Independent of whether the system is in a water-rich (1, 2), dry (3) or some state between these two extremes, lake water keeps the balance to sea water intrusion as long as the pressure of the freshwater island lens keeps the transition zone between salt and fresh water at substantial distance from the lake itself. Theoretically spoken (Ford and Williams 2007), if we take into account only the differences in density of salt (1025 kgm^{-3}) and fresh water (1000 kgm^{-3}) for certain average conditions which can be applied to the Adriatic coastal area as well, according to the above mentioned Ghyben-Herzberg hydrostatic rule the freshwater – saltwater transition zone would be 40 m below seal level in the case of 1 m upleveling of the freshwater lens. In reality, due to specific karstic environment with dynamic water level oscillations and underground water circulation, this transition zone gets much closer to the lake. Therefore, protection of the lake from saltwater intrusion regarding its lowest point at 61.3 meters below sea level requires a much higher hydrostatic pressure of freshwater column than the 1.53 m that can be calculated from the model described above.

Untill now minimum recorded water level of the lake was 9.11 msl, it continues to exist as a freshwater phenomenon. Performed modelings show that increase in water pumping to average annual 0.150 m^3s^{-1} in the given hydrological conditions, would cause minimum water level to drop at 6 msl, while the formerly planned pumping regime of 0.250 m^3s^{-1} would decrease the water level to just 2 msl. As these modelings give very significant extrapolations, eventual water pumping increments must be conducted with great caution and strict control (Ozanić and Rubinic 2001).

The lake shows great thermal stratification during the summer season. Chloride content, partly originating from the aerosol due to proximity of the sea, ranges between 62 and 92 mg/L and is quite homogenous throughout the water-body (Ozanić i Rubinic, 2001). To control the relation between underground and surface waters on the analyzed area, three boreholes were made in the lake's surrounding for measurements of lake's and underground water conductivity. Lake's water conductivity ranges from 370 to 460 μS/cm (with an average of 420 μS/cm in the surface layer and 400 μS/cm at the bottom), the biggest oscillations being recorded in the first 10 meters and ranging in the scope of 60 μS/cm. Deeper parts of the lake show lower variability, ranging in the scope of 25 μS/cm, and the zone below the thermocline shows practicaly constant values (400 – 404 μS/cm). Opposite from the lake's water, underground water conductivity measured in the boreholes increases with the depth of sampling, as well as with the distance from the lake, ranging from 440 to 600 μS/cm (IGI 2001).

These existing stable relations between fresh and salt water of Vrana Lake on Cres can be disturbed by excessive pumping for water supply, and on a larger time-scale by global rise of the sea level. Regarding recent indicators, most realistic models predict the sea level rise in the range of 0.9±0.3 mm/year (Pirazzoli 2000).

METHODOLOGY AND RESOURCES

Methodology used in this work is directly dependent on availability of the background data, mostly encompassing elementary hydrologic data (daily or characteristic yearly values) on registered water levels of sea and lake. Based on these data, simple statistical analysis are made to show data trends, interrelations and their autocorrelation functions (Salas et al 1990). The results of the analysis are interpreted in the context of freshwater – saltwater equilibrium maintainance in the coastal karstic aquifers.

When considering Vrana Lake in Dalmatia (Figure 3) water level data from the location III (Prosika canal – Vrana Lake) are used for the period 1948-2006, and registered sea level data at the Prosika canal estuary for the period 1986-2006. While analyzing Vrana lake on Cres (Figure 5), measured sea level data at location A (Vrana – Stanic) are used for the period of 1948-1977, and because of transfer of the hydrological station, data from location B (next to water intake and the hydrological station CP Vrana) are used for the period 1978-2006. It is interesting to note that for both lakes first monitorings of water level had begun in early 1928, which makes them localities with longest hydrological monitoring history in the coastal part of Croatia. But, due to unregistered and varying position of the „zero“ point of the water-scale at Vrana Lake in Dalmatia (location at the bridge over the Main canal), as well as to interruption of monitoring during the II World War, these earlier data were not adressed.

The idea of this work was to use simple analysis of elementary hydrological parameters, and through comparison and interpretation of the analysis results attain valuable indicators on functioning of the two largest water systems in Croatian karst area. Interpretations included also the results of certain hydrological observations of a broader range.

Results of Comparative Hydrological Analysis

The first step in performed analysis was to compare the oscillations of average daily water levels at the two analyzed lakes. Although water levels oscillate around different height points, Figure 7, showing the last twenty years period, points out general similarities and differences in the oscillation cycles. Seasonal annual exchange of water-rich and dry periods is obvious, showing shifts and slower reactions for the Vrana Lake on Cres, indicating a greater insertion in drainage and filling of the water reserves for this lake. But it can also be noted that during the extremely dry periods, such as in 1989-1990, both lakes reacted in quite the same way – with the absence of an otherwise common water period, prolonging the recession period during the winter time.

To be able to analyze interrelations of water level oscillations between the lakes and the sea, detailed overviews have been extracted for the above mentioned extremely dry period from 1990-1991 (Figure 8), as well as for one common, average water period at the end of the time period observed, from 2004-2005 (Figure 9). These overviews show sea level oscillations at the Prosika canal estuary into the sea, which directly influences the water oscillation regime of Vrana Lake in Dalmatia. Figures 8 and 9 also shows the position of the bottom of Prosika canal, designated for evacuation of excess water from the lake into the sea. Given overviews point out two important characteristics of the analyzed lake systems: to react in a similar way regarding the water level oscillations during the water-rich periods, but to express different reactions during the dry periods, Vrana Lake on Cres showing bigger inertion due to slower drainage of its aquifer. Vrana Lake in Dalmatia shows constant upleveling of lake's water level with respect to sea level, even in situations when the sea level is higher than the prague of the overflow canal. Only in the long-lasting extremely dry periods, such as was the one from middle 1990 till early 1991, when sea level exceeded the lake's level for up to 20 cm, the sea water entered into the lake system, causing high salinity values of lake's water, adressed above in this paper. Cases of occasional but short-term uplevelings of the sea above the lake and above the Prosika canal prague were recorded in several other years, but with smaller rises in salinity of the lake's water.

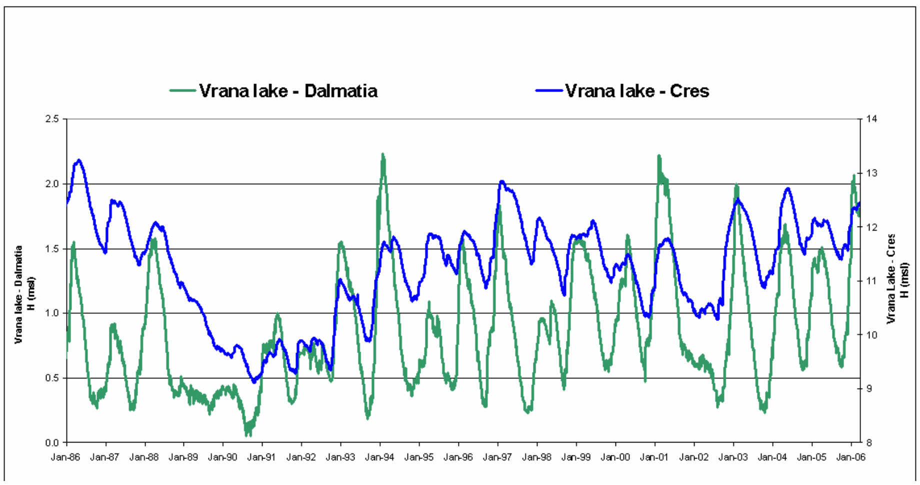

Figure 7. Comparison of daily water level oscillations for Vrana Lake in Dalmatia and Vrana Lake on the island Cres (1987-2005)

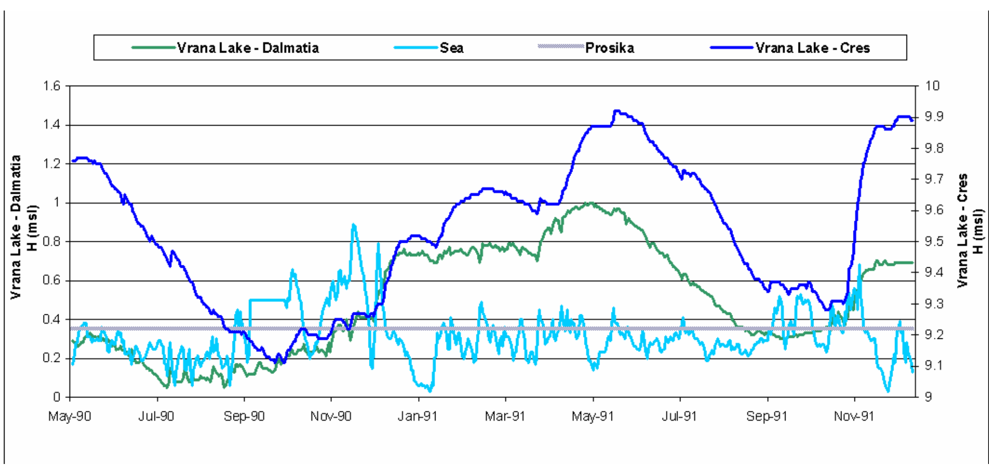

Figure 8. Comparison of daily water level oscillations between the analyzed lakes and the sea, for a very dry period 1990-1991.

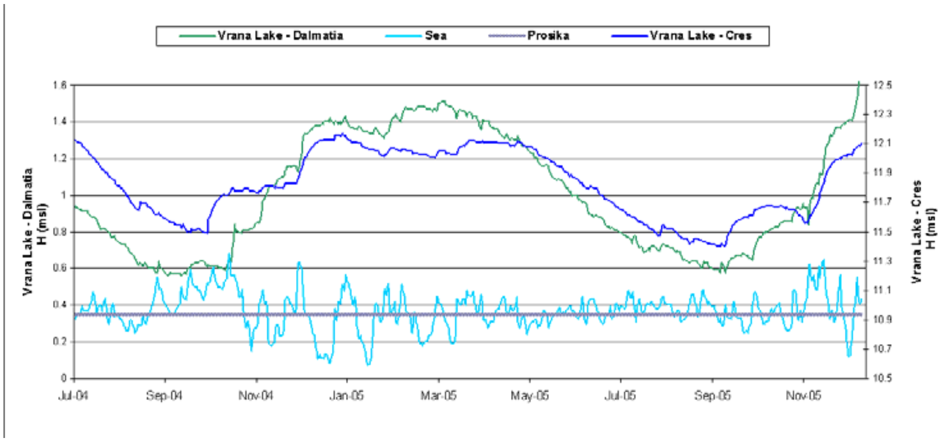

Figure 9. Comparison of daily water level oscillations between the analyzed lakes and the sea, for a common water-rich period 2004-2005

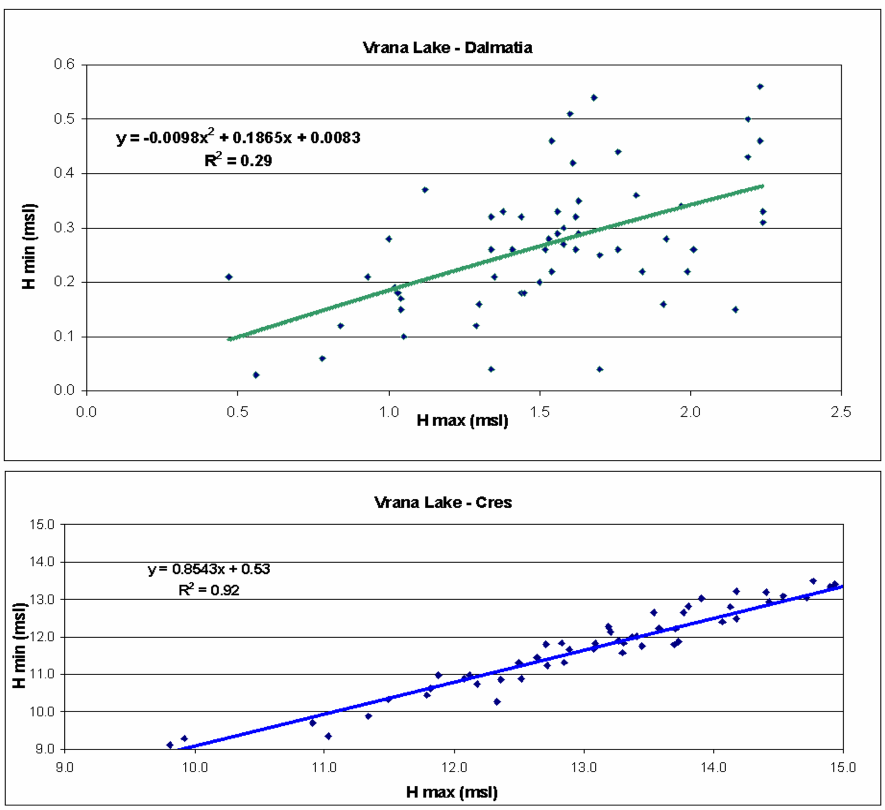

Figure 10. Analysis of minimum and maximum annual water levels interrelations in both lakes, during the period of 1948-2005

The described differences in reaction inertness of the analyzed lake systems can also be noted from the analysis of interrelations of maximum and minimum annual water level values (Figure 10), showing a much greater determination coefficient for Vrana Lake on Cres (R^2=0.92) than for Vrana Lake in Dalmatia (R^2=0.29), where it is of no statistical significance. This means that in Vrana lake in Dalmatia, even the plentiful water-rich periods can be followed by very low water levels in the dry period, with increased risk of water salification.

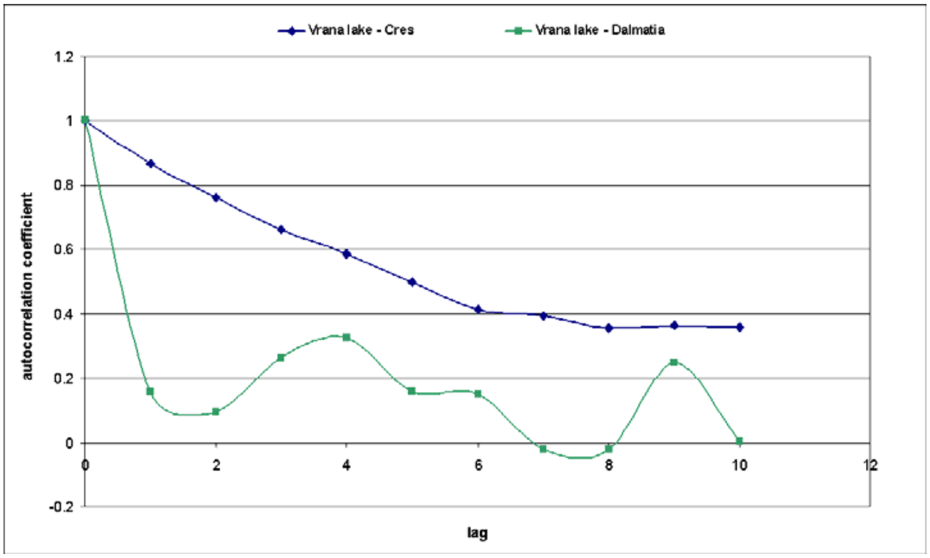

Figure 11. Autocorrelation functions of minimum annual water level values recorded in the analyzed lakes for the period 1948-2005

Additional confirmation of greater inertness of Vrana Lake on Cres is given in the Figure 11, demonstrating the autocorrelation functions of minimum annual water level values for both lakes. The figure shows a drop of autocorrelation coefficient in Vrana Lake in Dalmatia below the value of 0.2, generally taken as the limit value (Mangin 1984), immediately after the first autocorrelation step.

Finally, a comparative analysis of minimum annual water level oscillations is conducted for the entire analyzed period (Figure 12). The results, expressed as modular values for easier comparison, show very interesting interrelation of opposite trends in water level oscillation of the two analyzed systems.

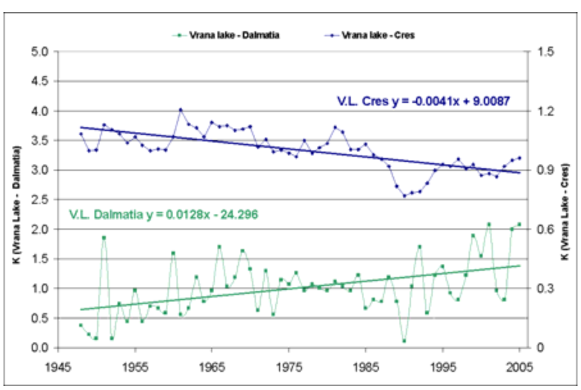

Figure 12. Comparison of trends in modular values of minimum water levels in the analyzed lakes (1948-2005)

Vrana Lake on Cres shows a trend of decrease in minimum water level values, which was to be expected considering the waterflow oscillation trends at a broader regional area (Rubinić et al 2007), as well as influence of water usage for water supply. Modular value of water level decrement trend amounts about 0.4%, that is 4.8 cm/year. Vransko Lake in Dalmatia shows a distinct trend of water level increment, although it is situated in the same regional area influenced by the mentioned waterflow decrement trends. Modular value for water level increment trend for Vrana Lake in Dalmatia amounts 1.3 %, that is 0.35 cm/year. This unusual trend can be related to several reasons: decrease in water usage from lake's catchment due to domicile war in the nineties, which is the least convincible assumption and decrease in water outflow due to irregular maintainance of Prosika canal, causing vegetation overgrowth of the canal and slowing down the drainage processes. In addition, the described trend can also be related to global rise in the sea level and consequent reaction of the lake system by the successive increment of water level at which the freshwater – saltwater balance can be established.

It is the example of Vrana Lake in Dalmatia that best shows negative influences of global rise in the sea level at a shorter time-scale. Opposite to relatively stable equilibrium of fresh and salt water in the Vrana Lake on Cres, Vrana Lake in Dalmatia suffers very low water levels during the dry periods, even lower than the sea level, inspite of the small depth of the lake (3 meters below sea level). In these situations the freshwater lens, normally preventing the propagation of sea water through the karst underground, thins out and allows intrusion of salt water in the lake's area, and in some cases even reverse surface flow of sea water through Prosika canal into the lake.

It is obvious that even the recent trends in rise of the sea level for 0.13 mm/year, detected for the period since 1969 at the mareograph located in Bakar, on the Croatian coast between the two Vrana Lakes (Faculty of Civil Engineering 2007), already cause significant problems of lake water salification for Vrana Lake in Dalmatia.

But if the excessive pumping would significantly decrease the average water level of Vrana Lake on Cres, this lake would also suffer the freshwater – saltwater equlibrium disruptance and even face the risk of sea water intrusion in the untill now freshwater karst system.

CONCLUSIONS

Analysis conducted in this work show how even simple observations of just one hydrological parameter (sea and lake water level), interpreted in the context of broader regional hydrological knowledge and available background data on lake salification monitoring, can give very inetersting and relevant conclusions related to the functioning of the analyzed lake systems.

Comparative analysis of hydrological characteristics of Vrana Lake in Dalmatia and Vrana Lake on the island Cres, conducted for the first time in this paper, demonstrated certain similarities, abut also differences in the behaviour of their hydrological systems. Although both lakes show very similar general seasonal cycling of water-rich and dry periods, hydrological system of Vrana Lake on Cres expressed greater inertion and slower reactions considering drainage and filling of its water reserves. Existing oscillations in water level, inspite the water usage for water supply, do not exceed the range of observed maximum values in which the stability of the lake system and prevention from sea intrusions can be guaranteed.

Vrana Lake in Dalmatia, on the contrary, has a very unstable equilibrium due to unfavourable height interrelations yet worsened by anthropogenic influence (digging through of the Prosika canal), which causes significant intrusions of sea water into the lake and its karstic aquifer during the dry periods. The existing regime of water usage from the lake is proved to endanger the lake system by salification of its waters. As a contribution to this, global trend in rising of the sea level induces the lake water level increment trend, inspite the global decrease of inflows.

Both lakes represent valuable natural resources, with specific ecological characteristics: Vransko Lake in Dalmatia as a unique wetland ecosystem inhabited by numerous endangered species, whose habitat directly depends on water level oscillation trends of the lake, and Vrana Lake on Cres is an isolated freshwater ecosystem with specific living community whose existence depends on maintainance of the fresh and salt water equilibrium in the lake. To prevent excessive salificaton of these ecosystems, which would have a fatal result on their living communities as well, it is important to improve and intensify the existing monitorings of hydrological parameters, water quality and ecological conditions of the analyzed lakes.

This work confirmed both lakes to be distinctly dynamical systems, which is an expected characteristic of karst lakes. The changes in their regimes are not linked solely to past geological periods, but are being detected in the present as well, and are to be expected in the future. Anthropogenic influences can significantly accelerate these processes, and in short-time periods additionally endanger the lake systems.

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