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Seiches in the Plitvice Lakes

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A campaign of high-frequency measurements of water level was carried in the two largest of the Plitvice Lakes, Prošće and Kozjak, to study seiches in the lakes. Measurements were performed at 1-min sampling rate during a 46-day interval, at two opposite ends in each lake, which also provided information on the phase relations. Power spectra were calculated to determine the periods of the normal modes. The observed peaks in the spectra were interpreted with the help of theoretical results obtained by the simple numerical method of Defant, where two different historical bathymetries were used. The lake Prošće oscillates at the periods of 8.5 min, 5.0 min, 3.3 min and 2.2 min, the oscillations being related respectively to uni-, bi-, three- and five-nodal seiche modes, whereas the four-nodal mode (2.5–2.7 min) was not significant during the experiment. The lake Kozjak oscillates at 9.0 min, 4.9 min and 2.6 min, which corresponds respectively to the uni-, bi- and four-nodal mode, the five-nodal mode is likely at the period of 1.9 min, while the three-nodal mode (~ 3.4 min) was not generated; the deeper sub-basin displays its own principal mode at the period of 2.3 min. The discrepancy between the observed and the calculated periods is attributed to poor representation of the basin by the historical bathymetries, especially at Prošće, but also to changes in basin depth, due to continuous process of tufa growth.

Keywords: Plitvice, seiches, periods, bathymetry, tufa growth

1. Introduction

The Plitvice Lakes, situated in the Dinaric karst area of central Croatia, are a unique system of 16 lakes barraged by tufa barriers forming cascades and waterfalls. The lakes are part of the Korana River valley. The height difference between mean water level of the first and the last lake is 134 meters. The Upper Lakes are formed on unpermeable dolomite and are set in a wide valley of gently sloping sides, while the Lower Lakes are cut into a deep canyon of porous limestone. The largest two, Prošće and Kozjak, are the first and the last in the series of the Upper Lakes. Largest amount of water is supplied by the Matica River which enters Prošće, and by the Rječica River, a tributary to Kozjak. Water leaving the last of the Lower Lakes joins the Plitvice River to form Korana River.

The Plitvice Lakes are formed and maintained by tufa deposition. The process takes place in highly specific conditions. Due to geological base and environment, water is of particular chemical characteristics (supersaturated in calcium bicarbonate, pH value above 8 and low concentration of organic matter) and when dispersed into droplets the mineralization of calcium carbonate takes place (Srdoč et al., 1985). The water is abundant in moss, algae, detritus and microorganisms which retain the crystals and promote their agglomeration. The tufa growth is intensified during warmer periods.

Different chemical, physical and biological aspects of this complex and susceptible system have been studied. Carbonate isotopes were used to study processes influencing calcite precipitation (Barešić et al., 2011) and environmental changes (Horvatinčić et al., 2008). Anthropogenic impact was identified through indicators of untreated wastewater found in lake sediments (Babinka, 2007; Mikac et al., 2011). However, the cascading system of the lakes has a self-purification efficiency to remove most trace and ecotoxic heavy metals from the aqueous phase (Dautović et al., 2014) and can generally be regarded as a clean ecosystem (Vukosav et al., 2014). The flow velocity has significant impact on distribution of particulate matter (*e.g.* Špoljar et al., 2007), organisms (*e.g.* Matoničkin Kepčija et al., 2011; Sertić Perić et al., 2014) and dead-leaf decomposition (Belančić et al., 2009).

Generally, geomorphology and physical factors, more specifically the water depth, bed slope, the flow velocity, turbulence and mixing, play a significant role in tufa deposition (*e.g.* Chen et al., 2004; Florsheim et al., 2013) and knowing the hydrodynamic characteristics of the water flow is of particular interest. Here we focus on hydrographic and hydrological issues. From the historical studies, whose exhaustive review may be found in Rubinić et al. (2008), the works of Gavazzi (1919) and Petrik (1958) are of special concern for this study. Based on his observations, Gavazzi analysed vertical temperature distribution and internal waves in the lakes. Moreover, he used the method that Defant (*e.g.* Defant, 1961) proposed only shortly before to theoretically estimate the principal-mode periods of the two largest lakes, Prošće and Kozjak, which required the basins' shapes to be evaluated. During several years in 1950's Petrik carried out extensive interdisciplinary measurements. Significant effort was made to establish a detailed bathymetry of the major lakes and to determine the total water flow. For decades his work served as a hydrological base in various studies and the measuring stations established at the time are now used to continuously monitor changes in the hydrological system (Rubinić et al., 2008).

As a result of tufa deposition, the lakes' beds elevate and the height of the barriers increases, continuously changing the morphology of the basin. Generally, the barriers gain height at a much higher rate than the bottom is being covered with deposits (Srdoč et al., 1985) and over time the water level rises changing the lake volume. The process is not uniform and each lake has its own dynamics.

Srdoč et al. (1985) have assessed that over the last 700 years or so, the water level in Kozjak has been rising at the rate of 1.35 cm/year. Rubinić et al. (2008) report, over the period 1952–1990, the rise of 0.56 cm/year for Kozjak, and estimate about three times faster rise at Prošće; at the same time, the water flow at Plitvice experienced a significant reduction, the largest in the Croatian karst. The decreasing trend became even more pronounced in the period 2001–2011, especially at minimum flows (Bonacci, 2013). The reduction of the water flow has also effected the water-level trends in Prošće and Kozjak, as well as their mutual relationship (Rubinić et al., 2008; Bonacci, 2013). However, the behaviour is strongly influenced by strong climatic fluctuations experienced in recent years.

The aim of this work is to study standing waves (seiches) of the Plitvice Lakes. Seiches are observed in enclosed or semi-enclosed bodies of water, as periodic rising and lowering of water level and swaying currents, with the period ranging from minutes to hours. They are usually induced by a jump in air pressure or abrupt change in wind (*e.g.* Pugh and Woodworth, 2014) when, upon cessetion of the forcing, water level returns from initial deformation to uninterrupted state through a series of normal modes. In order to determine the periods of the normal modes of the lakes Prošće and Kozjak, a campaign of special water-level measurements was organized in 2008. The empirical results are interpreted with the help of theoretical values derived by Defant's numerical method (*e.g.* Defant, 1961) and compared to the ones that Gavazzi (1919) obtained using crude bathymetry of the basins almost a century ago. Generally, the periods of normal modes are determined by the morphology of the basin, which in the Plitvice Lakes changes noticeably on the scale of hundred years. On one hand, in such circumstances the actual periods may with time acquire a different value. On the other hand, the theoretical estimation depends on the accuracy of the available bathymetry. Thus our empirical periods, which can be determined with high confidence, provide a good test for bathymetry used in elaborate hydrodynamical models, but may also serve as an indicator of morphometric changes that may occur over time.

2. Data and methods

A series of high-frequency water-level measurements was completed during a 46-day interval between 17 October and 4 December 2008, in the lakes of Prošće and Kozjak. The recordings were performed with a 1-min sampling interval, at two opposite ends of each lake (Fig. 1). Stations P1 and P2 are at Prošće while K1 is in the elongated, shallower part and K2 in the wider, deeper part of Kozjak. Measurements were also planned at the sill in the Kozjak Lake, but unfortunately the instrument there was malfunctioning. The instruments used were small pressure sensors with integrated data loggers (Hobo U20 Water Level Data Logger) fixed close to the lakes' bottom. Accuracy of the instrument expressed as water level is ± 2.1 cm. It should be noted that it records

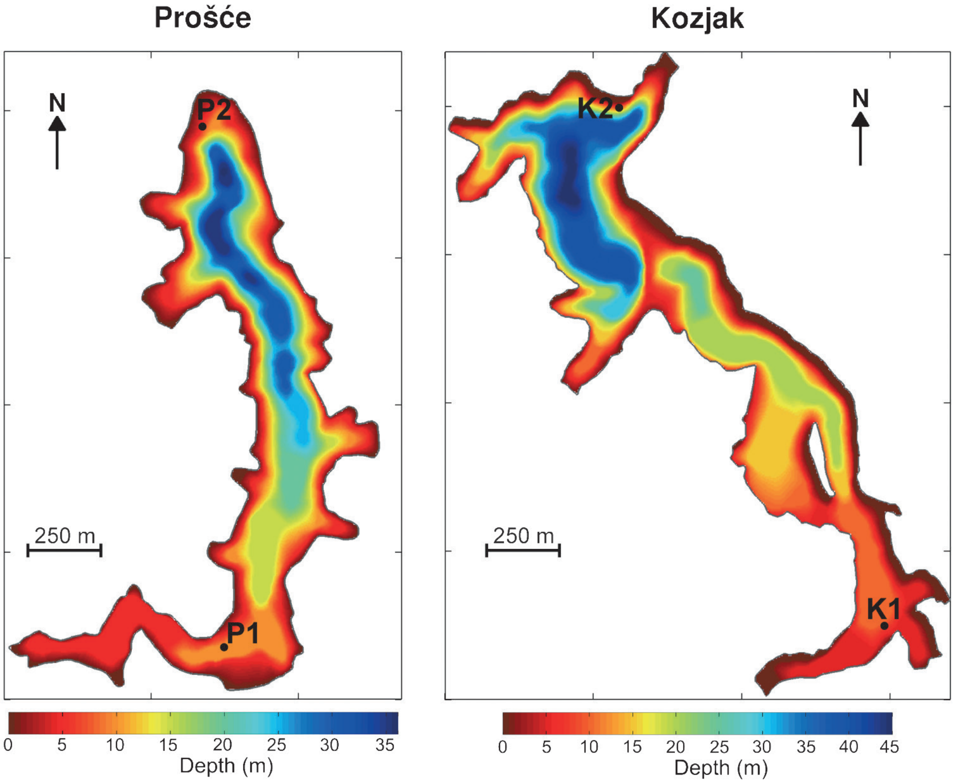

Figure 1. Bathymetry of the Prošće lake (*left*) and the Kozjak lake (*right*) derived from depth isolines given in Petrik (1958). Also shown is the position of the sites (P1, P2, K1 and K2) where high-frequency water-level measurements were performed.

instantaneous values and does not have the possibility of high-frequency sampling and averaging. The memory provides for some 3 weeks of 1-min data so during the observation period the instruments were once taken out to download the data; when returning they were placed on a slightly different position so there is a shift in the data of the first and the second interval. The pressure measurements were corrected for the effect of atmospheric pressure. The local air-pressure data were not available so the corresponding time series (Fig. 2., *top*) was constructed by averaging data from two nearest meteorological stations (Ogulin and Gospić). Upon subtraction of the atmospheric pressure, the pressure measurements (p) were converted to water level ($\varsigma + h$) using the hydrostatic pressure equation, $p = \rho \cdot g \cdot (\varsigma + h)$, where ς denotes departure from unperturbed water level h, ρ is water density and g is local gravity acceleration.

Oscillations of water level around zero level were obtained by subtracting from each time series their means over the respective intervals (Fig 2., *middle*). The high-frequency variability in the time series, which is the subject of this

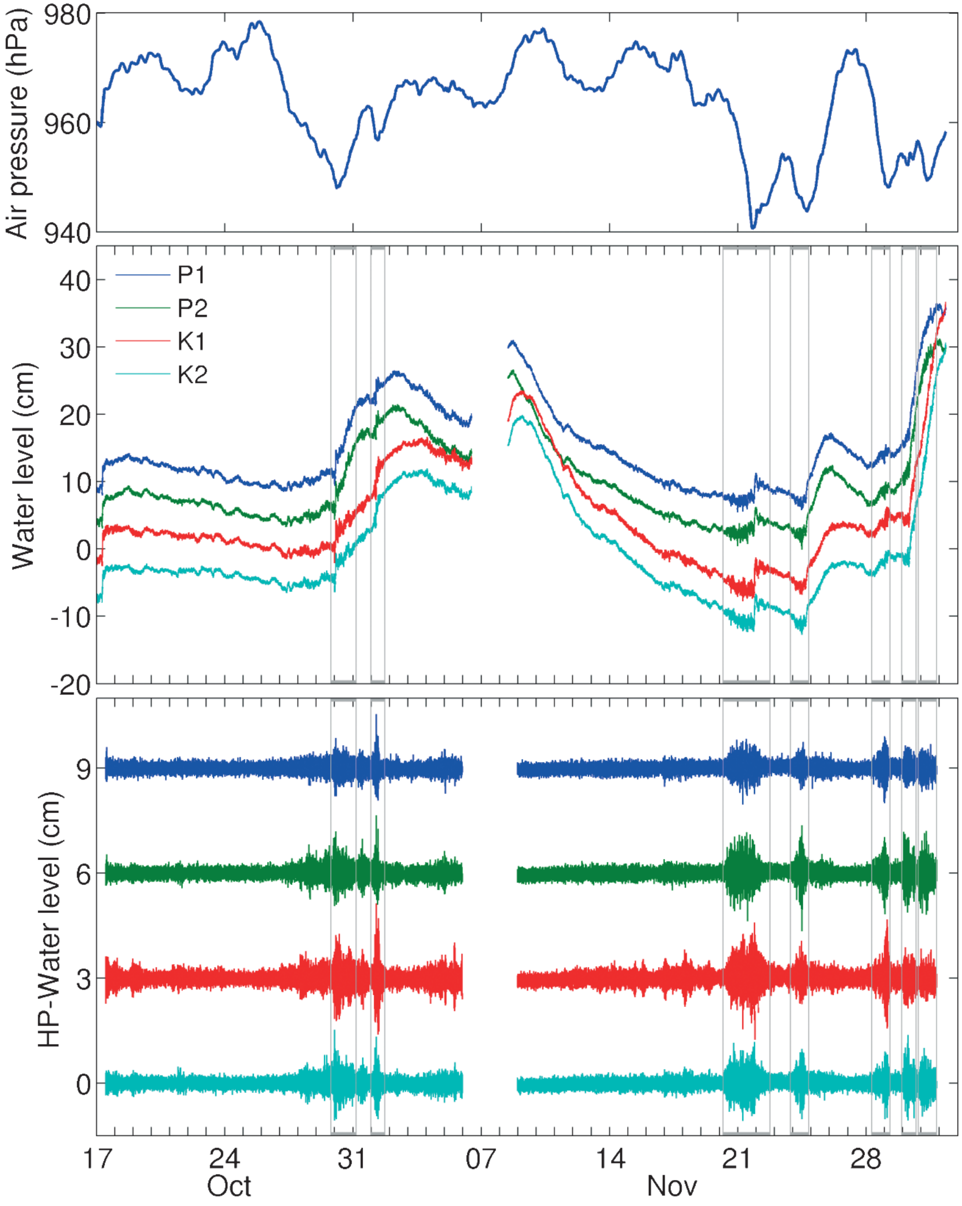

Figure 2. Water level and air pressure during the observational campaign, from 17 October to 2 December 2008. Air pressure obtained by averaging the data measured at two meteorological stations (Ogulin and Gospić) nearest to Plitvice (*top*). Water level registered at Prošće (P1, P2) and Kozjak (K1, K2) (*middle*) and the respective high-frequency water-level oscillations (*bottom*), both drawn with an offset. The grey lines indicate seven episodes of intense seiche activity.

study, was extracted by subtracting the data smoothed by 60-min moving average (Fig 2., *bottom*). The time series were analysed in time and frequency domain. Power spectra were calculated by the Welch method for the two recording subintervals and averaged, to determine the periods of the lakes' seiches.

In addition to the time series of water level at the opposite ends of the lakes, we also analyse time series of their differences and their sums, which enhance respectively the out-of-phase oscillations related to the odd modes and the in-phase oscillation related to the even modes of lakes' seiches. But, when interpreting these results, it should be kept in mind that the measuring sites were not positioned right at the tips of the basins.

The empirically obtained values are compared to the theoretical periods of lake seiches in a rectangular basin of length L and flat bottom of depth H. The period of the k-th lake mode, according to the Merian's formula (*e.g.* Sverdrup et al., 1942) is:

$$T_k = \frac{2L}{k\sqrt{gH}} \cdot \tag{1}$$

In order to account for a more realistic shape of the basins, a modification of Defant's simple numerical method (Orlić, 2010) is applied to determine the periods and spatial distribution of water level related to the lakes' uni-, bi-, three-, four- and five-nodal seiche. The elongated basin is approximated by an odd number of vertical cross-sections ($i = 0, \ldots, 2n$). The solution for water level and along-basin velocity is presumed in oscillatory form with period T and spatially dependant amplitudes Z and U, respectively. The velocity is calculated at even, and water level at odd cross-sections using the recursive relations:

$$\left.\begin{aligned} U_{i+1} &= \frac{S_{i-1}}{S_{i+1}} \cdot U_{i-1} + dx_{i+1,i-1} \cdot \frac{2\pi}{T} \cdot \frac{b_i Z_i}{S_{i+1}}, && \text{for } i = 1, 3, \ldots, 2n-1 \\ Z_{i+1} &= \frac{dx_{i+1,i-1}}{g} \cdot \frac{2\pi}{T} \cdot U_i + Z_{i-1}, && \text{for } i = 2, 4, \ldots, 2n-2. \end{aligned}\right\} \tag{2}$$

Here S_i is the area, b_i the width and $dx_{i+1,\,i-1}$ the along-basin distance between vertical cross-sections. In order to accommodate for the boundary condition of no flow through the fixed boundary, the velocity U_0 at the first closed end is prescribed to zero and the water level Z_1 is set to an arbitrary value that is determined by initial conditions. The recursive relations are used to obtain the velocity at the other closed end (U_{2n}). The calculation is performed with T varying over an interval of values and the obtained velocities U_{2n} are plotted against T; the points of zero crossings give the periods of the normal modes.

The above calculation strongly depends on the shape of the basin. Here, two presently available bathymetries for the two lakes, namely from Gavazzi (1919) and from Petrik (1958), are used. Gavazzi discretized the Prošće basin with 16 vertical cross-sections and Kozjak with 14 cross-sections. In the first calculation we took his numerical values for areas of the vertical cross-sections and the distances between them and, in order to minimize computational errors, interpolated them to 101 equidistant cross-sections using the Akima (Akima, 1970) method. In the second calculation, the bathymetry was constructed by digitizing the isobaths given by Petrik, and interpolating them bilinearly on a 10 m × 10 m grid; the obtained depths were used to calculate the areas of 65 vertical cross-sections at Prošće and 67 cross-sections at Kozjak.

3. Results

Time series of water level recorded at the four stations, drawn with an offset, are shown in Fig. 2. The most pronounced feature is the synoptic-scale variability of some 40 cm range that occurs simultaneously at all the sites. It is likely related to changes in the water supply from the Matica and Rječica rivers, numerous creeks and surface runoff. However, the focus here is on high-frequency oscillations that are observed as small-amplitude perturbations on the low-frequency variability. During the experiment we can identify several intervals with seiche activity within the lakes, lasting around 18 hours. Over the longer episodes, like the one from 20 to 22 November, after the initial excitation, there were one or several further inputs of energy. The onset of maximum seiche activity each time coincides with a sharp change of air pressure (Fig. 2, *top*) which is usually related to a passage of a weather front and is accompanied with abrupt change in wind.

The high-frequency oscillations related to an episode of seiches are shown in Fig. 3. The seiches do not contribute significantly to the overall water-level variability in the lakes, as their amplitudes are only some 1–2 cm. Even at K1, where the oscillations were largest, the amplitude does not surpass 3 cm. In Kozjak the dominantly excited is the principal mode. In Prošće the oscillations are of a shorter period. Further, the sum of water level at P1 and P2 is larger than either of the time series, hence in Prošće second mode is induced with comparable amplitude to the principal one. Similar behaviour is observed during the other episodes, except in episode 3 when in Kozjak notable higher-mode oscillations are also evident (not shown).

Power density spectra clearly distinguish the periods of the principal mode and a series of higher modes. It should be mentioned that the peaks emerge consistently at the same frequencies, but with varying amplitudes, in the spectra computed from the overall time series and from the seven singled-out seiche episodes (not shown). The spatial structure of water level related to each peak may be inferred from the power spectra of the water-level differences and sums.

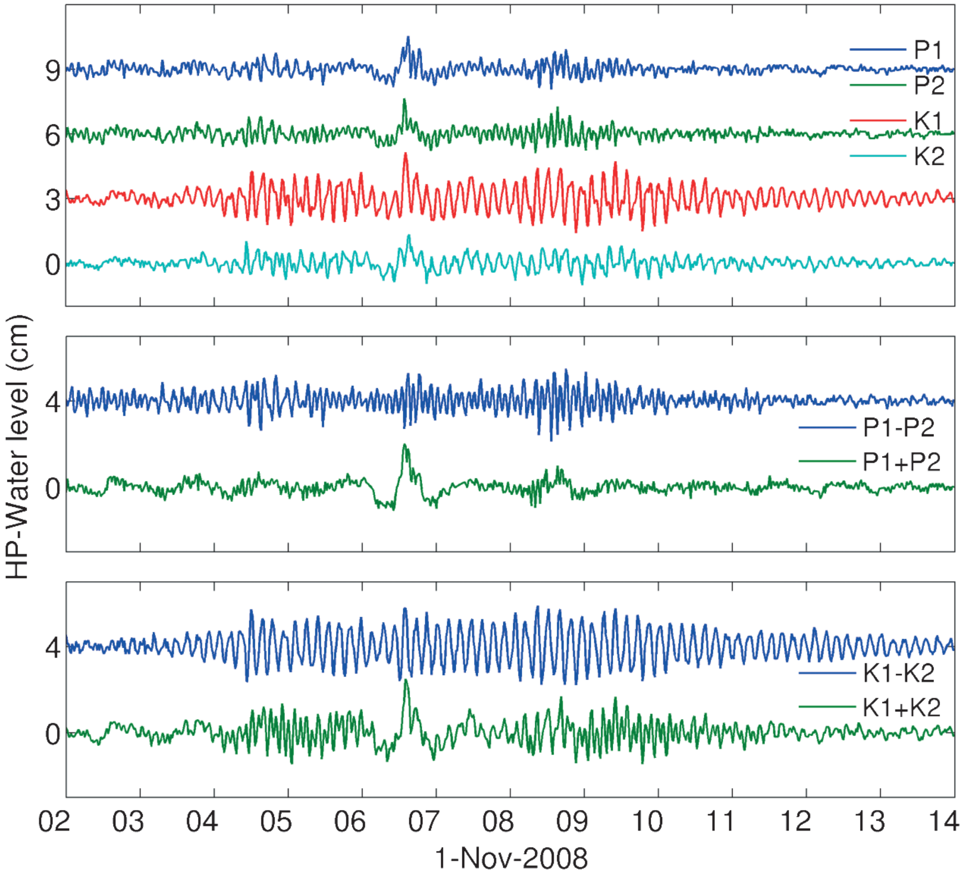

Figure 3. The high-frequency water-level oscillations during the seiche episode on 02 Nov 2008, from 02:00 to 14:00 CET. The time series at P1, P2, K1, K2 (*top*), the difference and the sum of the time series at the two opposite ends of Prošće (*middle*) and Kozjak (*bottom*).

3.1. The Prošće lake

Prošće oscillates at the periods of 8.5 min, 5.0 min, 3.3 min and 2.2 min (Tab. 1 and Fig. 4, *top*). The first two maxima are pronounced at both stations (P1 and P2), the one at 3.3 min is observed more distinctly at P1, while that at 2.2 min appears exclusively at P2. An increase in energy is also apparent at 2.7 min and 2.5 min, at P2. As already anticipated from the time series, the second mode often partakes with more energy than the first one. It is expected that in the power spectra of the differences and the sums of water level at the two ends, the first maximum will be enhanced for the differences time series, and then alternately,

Table 1. The periods of the Prošće lake: (i) significant peaks in the power spectra of Fig. 4, with the non-significant ones given in brackets. Periods of the first five modes of seiches obtained (ii) from the Merian's formula for L = 2927 m, H = 10.7 m, (iii) by the Defant's method applied to 101 cross-sections, interpolated on the data from Gavazzi (1919) and (iv) by the Defant's method applied to 65 cross-sections derived from the bathymetry of Petrik (1958).

	T_1 (min)	T_2 (min)	T_3 (min)	T_4 (min)	T_5 (min)
(*i*) Observed	8.5	5.0	3.3	(2.7, 2.5)	2.2
(*ii*) Merian's formula	9.5	4.8	3.2	2.4	1.9
(*iii*) Defant's method, bathymetry Gavazzi	7.3	4.5	2.7	2.0	1.9
(*iv*) Defant's method, bathymetry Petrik	9.6	5.5	3.5	2.7	2.2

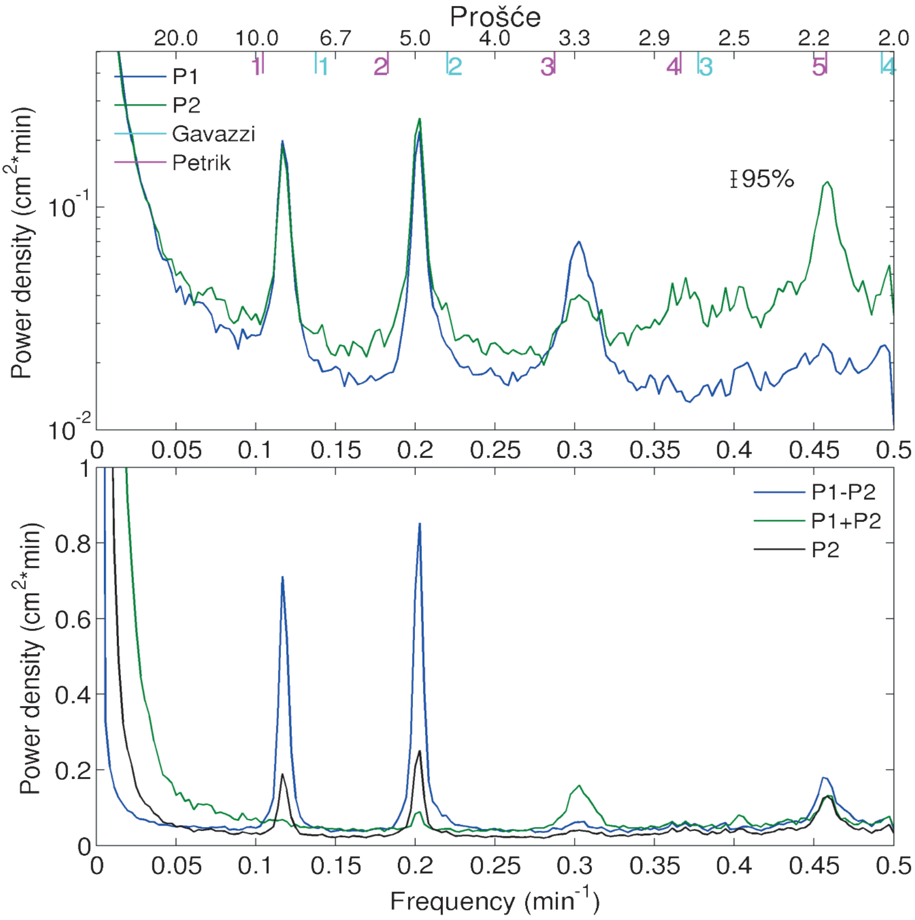

Figure 4. Power spectra of water level at Prošće: of the time series at P1 and P2 (*top*) and their differences (P1 - P2) and sums (P1 + P2) (*bottom*). The error bar indicates the 95% confidence interval. Numbers on the upper horizontal axis are periods in minutes. The theoretical periods for the first four/five modes, obtained with the two bathymetries, are marked by vertical lines on the upper horizontal axis.

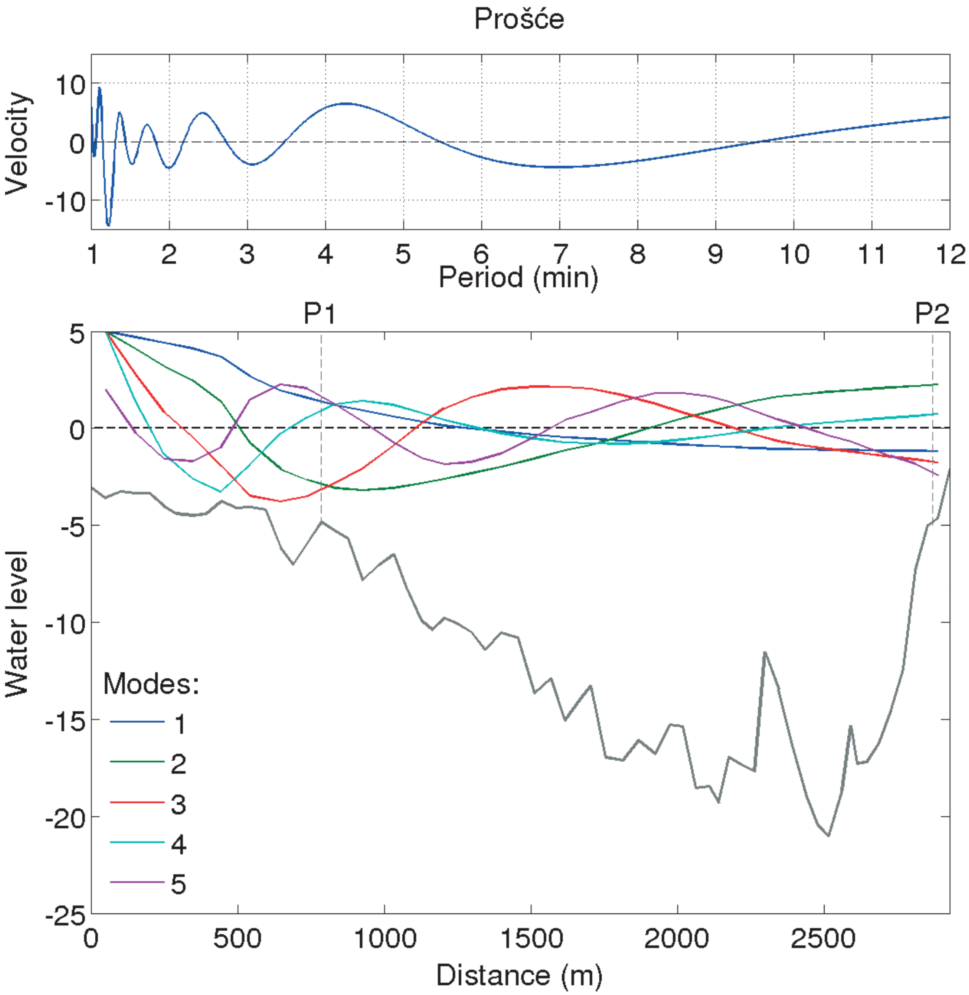

Figure 5. The theoretical results for Prošće, obtained with the Defant's method and the bathymetry from Petrik (1958): velocity at the final cross-section as a function of trial period (*top*) and distribution of maximum water level along the basin for the first five modes (*bottom*), with the periods equal to respective velocity zero-crossings. Units for velocity and water level are arbitrary. For better presentation different scaling is used for various modes and for along-basin water depth (grey line); the labels along the vertical axis refer to mean depth (in meters). Position of the measuring sites is indicated by P1 and P2.

for the sums and the differences. However, this is not the case for our data at Prošće (Fig. 4, *bottom*), where the first and the successive peak are both stronger in the differences than in the original time series. Such behaviour is probably because the station P1 is positioned rather far from the tip of the basin and the nodal line of the second mode is formed between the station and the basin end.

For a basin 2927 m long and 10.7 m deep (the values estimated from the data of Petrik), the Merian's formula (1) gives the periods (Tab. 1) which generally agrees with the observed. The periods of the first five modes obtained by the Defant's method, when applied on the refined bathymetry from Gavazzi (1919), are reported in Tab. 1. The principal mode is equal to what Gavazzi obtained with 16 cross-sections. The first and the second mode correspond fairly well with the observed, but the discrepancy is larger for the higher modes. Generally, the periods estimated with Gavazzi's bathymetry are shorter than the presently measured ones (Fig. 4). When using the same method, but the more elaborate and more recent bathymetry of Petrik (1958), the values obtained for the first and the second mode (Tab. 1) somewhat overestimate the observed peaks (Fig. 4); for the third mode it is very close to the observed one, while the period of the fifth mode coincides with the fourth maximum in the power spectrum. However, the calculated fourth mode does not have a distinct counterpart in the data power spectrum.

The distribution of water level along the basin related to the seiche modes at these periods is shown in Fig. 5, *bottom*. Also shown are the positions of the measuring sites. The principal-mode oscillations at P1 and P2 are of comparable amplitude and out of phase, as expected from the power spectra where the corresponding maximum is larger for the differences than for the original time series (Fig. 4, *bottom*). The nodal line for the second mode is formed beyond the P1 station, hence the oscillations at P1 and P2 are out of phase. This explains the apparently peculiar behaviour in the spectra that the second mode is again enhanced for the differences, and not for the sums. The third-mode oscillations are in phase and somewhat larger at P1, in accordance with the observations. For the four-nodal seiche, the amplitudes at the sites of P1 and P2 are rather small; at the corresponding frequency in the power spectrum no significant peaks, but only slight increase of energy is observed. The five-nodal oscillations are out of phase and larger at P2 than at P1; these features together with the calculated period well reproduce the highest-frequency maximum in the spectra.

3.2. The Kozjak lake

Water-level spectrum at Kozjak exhibits three distinct peaks, at the periods of 9.0 min, 4.9 min and 2.6 min (Tab. 2 and Fig. 6, *top*); an additional peak emerges at the period of 2.3 min at K2 and at 2.1 min at K1. A faint increase in energy may be noticed around 3.6 and 3.1 min. The maximum at 9.0 min, with the out-of phase oscillations at K1 and K2 (Fig. 6, *bottom*), corresponds to the lake's principal mode. The peaks at 4.9 min and 2.6 min are respectively related to the in-phase and the out-of-phase oscillations. The sharp maximum at the period of 2.3 min is observed only at K2, but no sign of it is detected at K1, suggesting that this is a normal mode of the deeper and shorter part of the Kozjak lake, downstream from the underwater barrier.

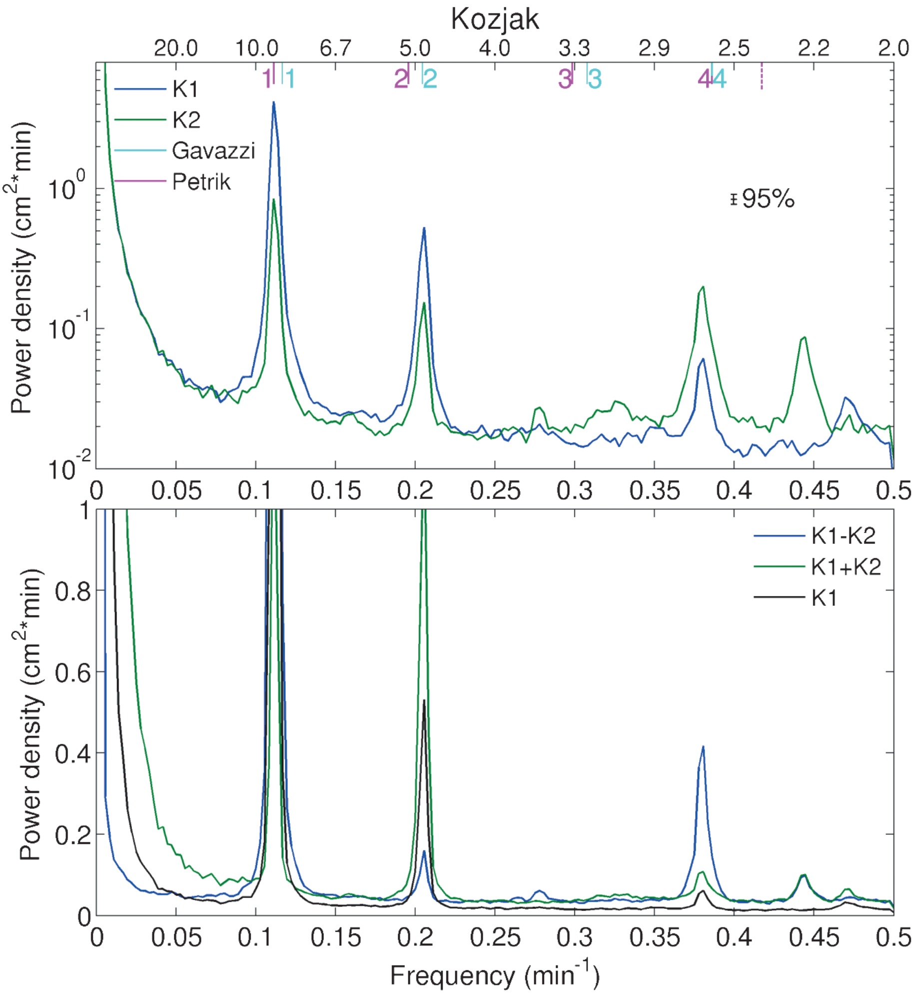

Figure 6. The same as in Fig. 4, but for Kozjak. The dashed line on the upper horizontal axis corresponds to the calculated first-mode period of the deeper sub-basin.

The Merian's formula, with the dimensions estimated from the Petrik's bathymetry, gives the periods which are on the order of the observed ones (Tab. 2). The periods determined by the Defant's method and the interpolated Gavazzi's bathymetry are much closer to those measured (Tab. 2 and Fig. 6, *top*). The principal and the second mode are very well reproduced. At the period of the three-nodal mode (3.3 min), no significant maximum appears in the power spectra. However, the period for the four-nodal mode coincides with the third observed maximum. It is noteworthy that the calculated period for the fifth mode is 1.9 min, which is shorter than that corresponding to the Nyquist frequency

Table 2. The periods of the Kozjak lake: (i) significant peaks in the power spectra of Fig. 6, with the non-significant ones given in brackets. Periods of the first five modes of seiches obtained (ii) from the Merian's formula for L = 3066 m, H = 13.2 m, (iii) by the Defant's method applied to 101 cross-sections, interpolated on the data from Gavazzi (1919), (iv) by the Defant's method applied to 67 cross-sections derived from the bathymetry of Petrik (1958); (v) first-mode period of the model covering only deeper sub-basin with station K2.

	T_1 (min)	T_2 (min)	T_3 (min)	T_4 (min)	T_5 (min) K2/K1
(*i*) Observed	9.0	4.9	(3.6, 3.1)	2.6	2.3/2.1
(*ii*) Merian's formula	9.0	4.5	3.0	2.2	1.8
(*iii*) Defant's method, bathymetry Gavazzi	8.6	4.9	3.3	2.6	1.8
(*iv*) Defant's method, bathymetry Petrik	9.0	5.1	3.4	2.6	1.9
(*v*) Sub-basin with K2, Defant's method, bathymetry Petrik	2.4				

(0.5 min^{-1}). The periods obtained with the bathymetry from Petrik (Fig. 7, *top*) are close or equal to the previous ones, with similar agreement with the observed peaks (Fig. 6, *top*). The computed distributions of water level (Fig. 7, *bottom*) related to the uni-, bi- and four-nodal mode are consistent with the phases and amplitude ratios at stations K1 and K2 that are inferred from our measurements. As for the three-nodal mode, the amplitude at the position of K2 is close to zero, while at K1 it is somewhat higher. An additional model covering only the deeper sub-basin north of the underwater barrier was applied, in order to see whether the observed maximum at the period of 2.3 min, which appears exclusively at K2, is a mode of that part of the lake. The period of the principal mode from the model is 2.4 min (Tab. 2, *bottom*).

4. Discussion and conclusions

The periods of normal modes of the lakes Kozjak and Prošće are determined empirically, from 1-minute instantaneous measurements of water level, and are calculated by the Defant method, using two sets of bathymetry data. The first (Gavazzi, 1919) is based on depth measurements in 1912, and the second (Petrik, 1958) on surveys made from 1951 to 1954. Generally, the agreement between the observed and the calculated periods is much better for the lake Kozjak than for Prošće. The use of Gavazzi's bathymetry, when interpolated on 101 cross-sections, produced better results than the one used by Gavazzi. However, when the bathymetry from Petrik is used, the estimated periods describe surprisingly well the observed ones, having in mind the simplicity of the Defant's method. When the observed maxima in the power spectra and the relative phases at the two

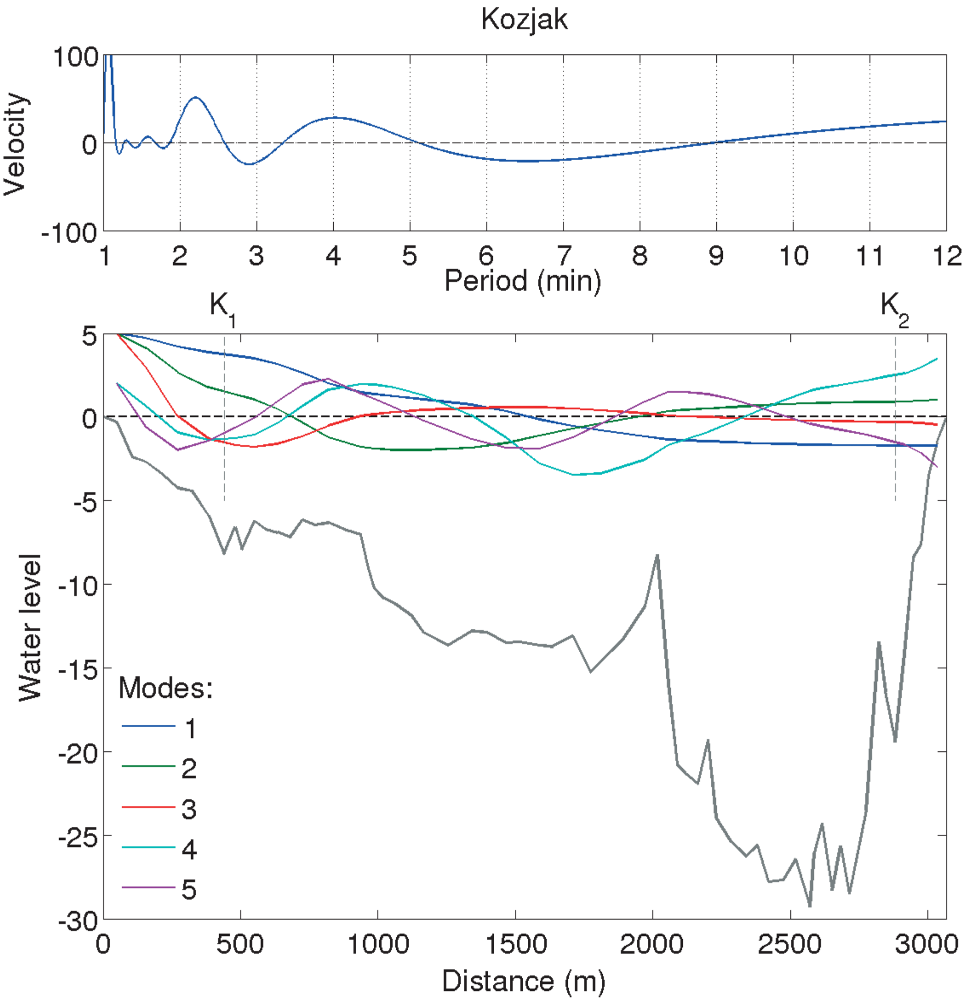

Figure 7. The same as in Fig. 5, but for Kozjak.

stations are compared with the calculated periods and the related water-level distributions along the lakes, the results can be summarized in the following: At Prošće, the first three maxima (8.5 min, 5.0 min, 3.3 min) are respectively periods of the uni-, bi- and three-nodal mode, the fourth maximum (2.2 min) is related to the five-nodal mode, whereas the four-nodal mode (2.5–2.7 min) was not significant during the experiment. At Kozjak, the first three peaks (9.0 min, 4.9 min, 2.6 min) are respectively the periods of the uni-, bi-nodal and four-nodal mode, while the three-nodal mode (~ 3.4 min) was not generated. The maximum at the period of 2.3 min is the principal mode of the deeper sub-basin.

Still puzzling is the origin of the maximum at 2.1 min, which is clearly visible at K1. It should be remembered that, due to the sampling technique, our water-level measurements may be affected by aliasing. For some frequency f below the Nyquist frequency (f_c), higher frequencies (f_o) which are aliased with f are given by (*e.g.* Bendat and Piersol, 1971):

$$f_0 = (2nf_c \pm f), \qquad \text{for } n = 1, 2, 3, ..., \tag{3}$$

where $f_c = 1/(2\,\Delta t)$. Accordingly, with the sampling interval $\Delta t = 1$ min, the lowest frequency which is aliased with the frequency 1/(2.1 min) is equal to 1/(1.9 min). The same value corresponds to the period that we obtained for the five-nodal mode. Hence, the peak at the period of 2.1 min is likely related to the five-nodal oscillations, which have the period of 1.9 min but, due to aliasing, emerge at the longer period.

It is interesting to note that, although the amplitudes of the high-frequency oscillations are on the order of a few centimetres, the distinct peaks in the power spectra clearly identify the principal and a number of higher modes. The lakes are surrounded by complex topography, and it may be expected that the wind there forms a non-uniform initial water-level distribution, giving rise not only the principal, but also to a number of higher modes.

Here several questions come forth: (*i*) why the agreement between the observed and the calculated periods is systematically better for Kozjak than for Prošće, although Kozjak has a much more complicated shape of the basin, (*ii*) why the results obtained with the two bathymetries differ more for Prošće than for Kozjak and (*iii*) is the discrepancy between the calculated and the observed periods due to the simple model and crude representation of the basins, or due to changes in their shapes that took place over the century. The answer to the first two questions may be attributed to the fact that the lakes have different dynamics of tufa deposition. At Prošće the rate of tufa growth is three times larger than at Kozjak (Rubinić et al., 2008), and it is likely that the morphology there has undergone greater changes since the time when the bathymetry was sampled. As to the third question, the rise of water level would mean reduction of the seiche periods. If we adopt for Prošće the rate of water-level rise of 1.5 cm/year, it would mean that the principal-mode period would reduce in 100 (50) years on the order of 0.6 (0.3) min. At the same time at Kozjak, with the rate of 0.56 cm/year, the period would reduce by some 0.2 (0.1) min. However, the presently observed periods at both the lakes are longer than the ones calculated with Gavazzi's bathymetry hence the discrepancy is due to inadequate basin shape. On the other hand the observed periods are shorter or equal to the values derived with Petrik's bathymetry so the small differences can partly be attributed to the increase of water level, especially at Prošće.

The presented results extend our knowledge on the two largest lakes of the complex and changing system of the Plitvice Lakes. In order to fully understand its dynamics, a detailed hydrodynamical model should be set up. This demands a good representation of the basin, and as a first test the model should be examined how it reproduces the observed normal modes. Furthermore, the detected periods can provide initial data for monitoring the changing bathymetry over time.

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SAŽETAK

Seši u Plitvičkim jezerima

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Poduzeta su visokofrekventna mjerenja razine vode u dva najveća plitvička jezera, u Prošću i u Kozjaku, kako bi se istražili seši. Mjerenja su rađena s intervalom uzorkovanja od 1 minute tijekom perioda od 46 dana i to na dva suprotna kraja u svakom jezeru, što je dalo informaciju i o međusobnom odnosu faza. Izračunati su spektri snage kako bi se odredili periodi vlastitih modova. Opaženi maksimimi su interpretirani uz pomoć teorijskih rezultata, dobivenih jednostavnom numeričkom metodom Defanta, pri čemu su se koristile dvije različite povijesne batimetrije. Jezero Prošće oscilira s periodima od 8,5 min, 5,0 min, 3,3 min i 2,2 min, što odgovara redom modu seša s jednom, dvije, tri i pet čvornih linija, dok se mod s četiri čvorne linije (oko 2,5–2,7 min) nije znatnije pobudio tijekom eksperimenta. Jezero Kozjak oscilira s periodima 9,0 min, 4,9 min te 2,6 min, što odgovara redom prvom, drugom i četvrtom modu, peti mod se vjerojatno odvija na periodu od 1,9 min dok se treći mod (~ 3,4 min) nije pobudio; dublji podbazen Kozjaka oscilira svojim vlastitim osnovnim modom na periodu 2.3 min. Neslaganje između opaženih i izračunatih perioda može se pripisati manjkavostima batimetrije kojom je opisan bazen, naročito u slučaju Prošća, ali i promjeni dubine jezera uslijed trajnog procesa rasta sedre.

Ključne riječi: Plitvice, seši, periodi, batimetrija, rast sedre

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