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SEASONAL CHANGES IN THE CERKNICA LAKE LEVEL DURING THE PERIOD 1961–2020

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Abstract

In this article, we analyse the annual changes in the minimum (Hnp), mean (Hs) and maximum (Hvp) water levels of Cerknica Lake in the period 1961–2020 and try to relate them to changes in the local climate. Lower precipitation, higher temperatures and the resulting higher evaporation as well as a reduced influence of snow retention are reflected in the changing discharge from the lake basin, which is a cause of a decrease in annual, spring and summer Hs and Hvp, while winter and fall Hs and Hvp have remained at a similar level. On the other hand, Hnp increases, except in spring, which is on an annual basis, in summer and fall (as far as the unreliability of data at the lowest water levels allows) probably due to artificial retention of water in the lake, and in winter and spring due to climate change.

Keywords: hydrogeography, climate change, changing water levels, lake water regime, Cerknica Lake, the Notranjska valley system, Dinaric karst

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1 INTRODUCTION

Climate affects a wide range of environmental processes and many areas of human activity. Although climate change is a natural phenomenon, the pace of climate change has increased disproportionately in recent decades due to greenhouse gas emissions (IPCC, 2022). Climate change is reflected in changes in a number of meteorological variables, including in Slovenia an increase in air temperature, changes in the amount, form and distribution of precipitation and a decrease in snow cover. Its effects are reflected in economic activities such as agriculture and forestry, energy, tourism, transportation, etc. (Vertačnik, Bertalanič, 2017), and in addition to the economy, water bodies and ecosystems are also highly vulnerable to climate change (Bertalanič et al., 2018; Trobec, 2022). Lake ecosystems are of critical importance for aquatic and riparian organisms and for a variety of human needs, so any change in the quantity or degradation of lake water quality can potentially have far-reaching ecological and societal consequences (George, 2010; Vincent, 2009).

In the present paper, we have chosen Cerknica Lake in the karst area of Cerknica Polje to study the effects of climate change on the hydrological properties of its waters. Due to its intermittent regime, Cerknica Lake is naturally highly variable in hydrological terms (Zhelezov et al., 2011). Due to their location at the interface between groundwater and surface water, intermittent karst lakes have a very complex hydrology, as their occurrence and water levels are influenced by a number of factors such as precipitation, snowmelt, evaporation, surface and groundwater inflow, groundwater reserves in the karst aquifer and groundwater outflow (Kovačič, 2010; Mayaud et al., 2019). In addition to natural factors, the discharge and thus the water levels of the intermittent karst lakes can also be influenced by various hydraulic engineering interventions on the watercourses, especially in the sinking part of the poljes (damming and special impoundments, widening of ponors, etc.) (Bonacci, 1987).

In our literature review, we came across a number of studies that examine the effects of climate change on the water balance and water quantity of lakes (e.g. Kayastha et al., 2022; Lenters, Kratz, Bowser, 2005; Torabi Haghigi, Kløve, 2015; Van der Kamp, Keir, Evans, 2008; Wrzesiński, Ptak, 2016), but there are few studies looking at the direct effects of climate change on changes in water levels of intermittent karst lakes (e.g. Morrissey et al., 2021). In Cerknica Lake, the change in water levels associated with climate change and anthropogenic interventions in the discharge regime was investigated by Miklič (2021) and Blatnik et al. (2024). The overall result is a positive and statistically significant trend in annual minimum water levels (Hnp), while the conclusions regarding the trend in mean (Hs) and maximum water levels (Hvp) differ due to the slightly different study period. The water balance of Cerknica Lake (Kovačič, 2010), the water regime (Zhelezov et al., 2011) and flooding (Kranjc, 1986) were also investigated.

In Slovenia, studies on the effects of climate change on the hydrological properties of surface waters have been conducted mainly on the water balance (Andjelov et al., 2021; Frantar, 2008), trends in various characteristic discharges in selected areas (e.g. Hrvatin, Zorn, 2020; Kovačič, 2016) and changes in river discharge regimes (Frantar, Hrvatin, 2005). A comparison of Slovenia's water balance at the level of the entire country for the period 1961–1990 and 1991–2020 shows a decrease in runoff height (by 120 mm) and runoff coefficient (by 3.5%) as a result of higher temperatures and evaporation and lower precipitation (Andjelov et al., 2021; Kolbezen, Pristov, 1998). The discharge trends of most Slovenian watercourses show a decrease in medium and low discharges and an extension of periods with low discharges, leading to hydrological drought, while on the other hand high discharges are more frequent and more pronounced (Kobold, Dolinar, Frantar, 2012). Comparing the periods 1961–1990 and 1971–2000, a decrease in peak discharge in spring and an increase in fall can be observed in the discharge regimes of rivers in Slovenia as a result of climate change. The number of discharge regimes has decreased, as have the differences between them (Frantar, Hrvatin, 2005).

The results of the above-mentioned suggest that the effects of climate change are also reflected in the water level of Cerknica Lake. The aim of this article is to examine the fluctuations in the mean annual and seasonal water level of Cerknica Lake over the 60-year period 1961–2020 and to draw possible parallels with climate change. For this period, we examined and presented the trends of annual and seasonal changes in air temperature, precipitation and snow cover in the area of Cerknica Lake and its immediate catchment, as well as the trends of mean (Hs), minimum (Hnp) and maximum (Hvp) annual and seasonal water levels of the lake and the minimum (Qnp), mean (Qs) and maximum (Qvk) discharge of the largest surface tributary – the Cerkniščica River. We also investigated the correlation between selected meteorological and hydrological variables.

Knowledge of the fluctuations in the water level of Cerknica Lake is important for the future dynamics of its intermittency and thus for the preservation of the already fragile, unique (peri-)aquatic and subterranean ecosystems characteristic of karst poljes (Bonacci, 2014; Gaberščik et al., 2003; Gaberščik et al., 2020). This is all the more important for Cerknica Lake, a world-famous intermittent karst lake in the heart of the Notranjska Regional Park, an important Natura 2000 and Ramsar site and an exceptionally diverse area in terms of geodiversity (Stepišnik, Ilc Klun, Repe, 2017). At the same time, the issue of changing water levels due to climate change is also important for successful adaptation to hydrological extremes such as floods and droughts and for the further economic development of the wider area (agriculture, tourism and other activities in the lake area).

2 PRESENTATION OF THE STUDY AREA

With an area of 38 km^2, the Cerknica Polje is the largest karst polje in Slovenia (Ravbar et al., 2021) and the central karst polje in a series of hydrologically connected karst poljes of the Notranjska valley system, which is an integral part of the Ljubljanica river basin (Figure 1). It lies between the higher Loško Polje in the southeast and the lower Planinsko Polje in the northwest. It is surrounded by the Javorniki Mountains to the southwest and the Slivnica and Bloke Plateau to the northeast. The bottom of the polje lies at an altitude of around 550 metres. The Cerknica Polje is characterised by the temperate continental climate of western and southern Slovenia (Ogrin, 1996). At the Dolenje Jezero climatological station, the mean annual air temperature in the period 1981–2010 was 8.9 °C (interpolated value from the climatological station in Postojna). In the same period, the mean annual precipitation at the precipitation station in Cerknica was 1552 mm (ARSO, 2022; Fig. 2).

Figure 1: Map of the Cerknica polje.

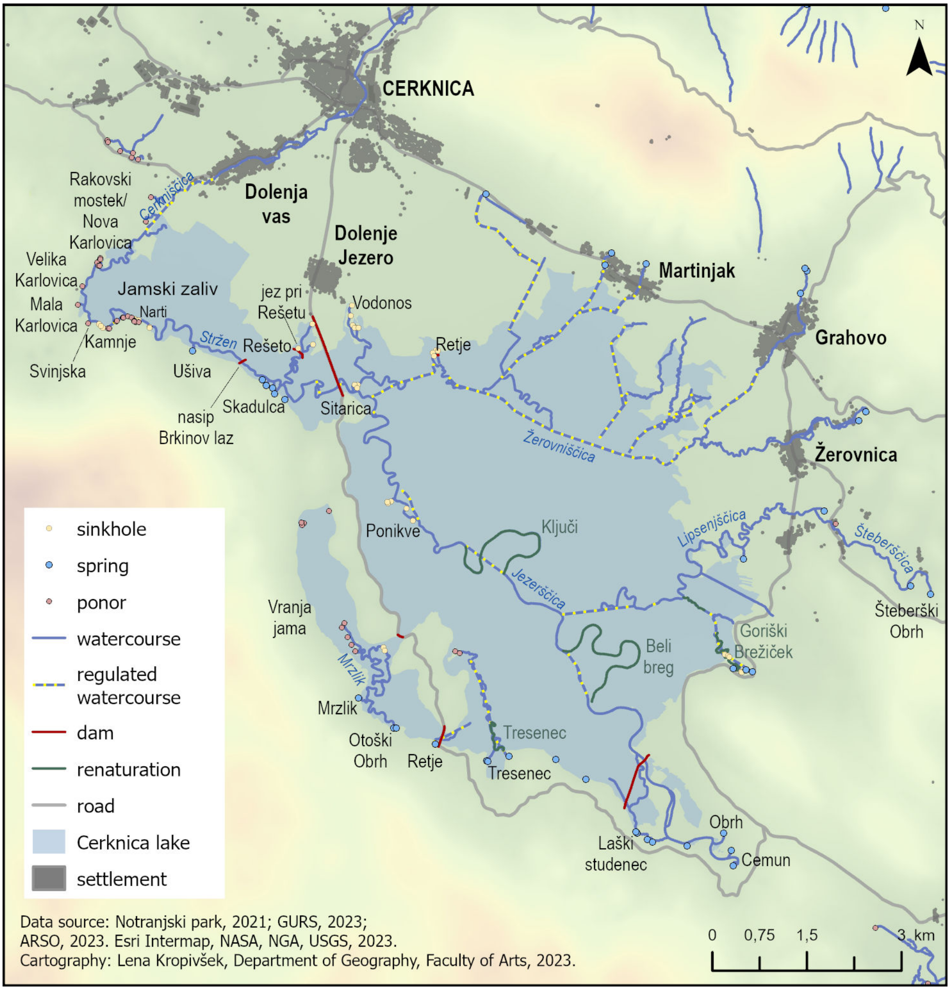
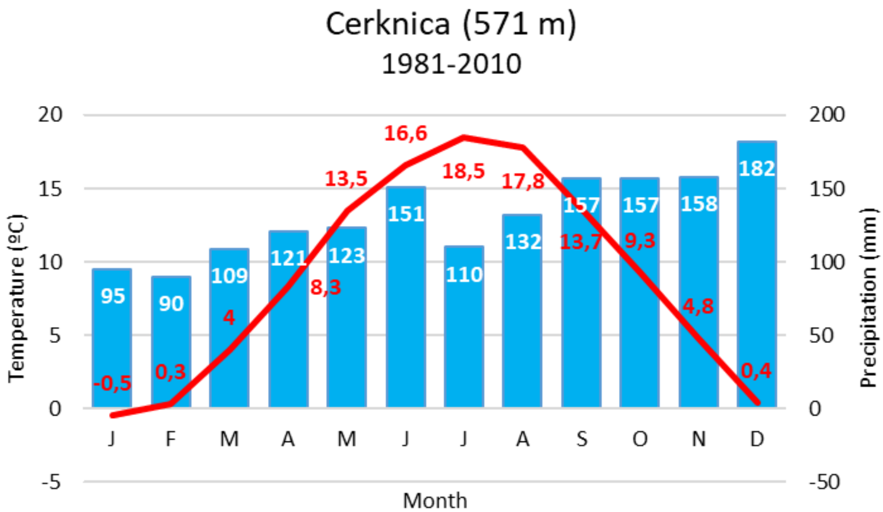


Figure 2: Climate diagram for the Cerknica meteorological station for the period 1981–2010.



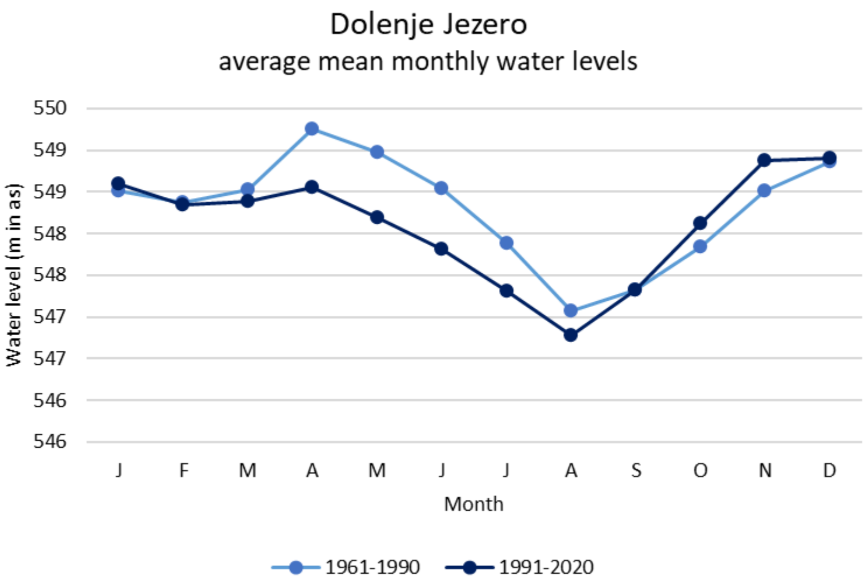
Source of the data: ARSO, 2022.

The Cerknica Polje is a combined type of border and spring-ponor polje (Gams, 1974) or a combination of inundated, overflow and inflow type polje (Stepišnik, 2020). The hydrological hinterland of the Cerknica polje is very diverse and extensive, with water from the Loško Polje and the Bloke Plateau flowing into the polje from underground (Kranjc, 1986) and the Cerkniščica River flowing into the polje from the surface. The catchment area of Cerknica Lake is 475 km^2. About 80 % of the area is fed by karst water and 15% by surface water, the rest comes from rainwater from the polje itself. Most of the karst watercourses flow from the eastern and south-eastern edges of the polje. The largest watercourse in the polje is the Stržen, which is called Obrh at its source. In the eastern part of the polje, the largest tributaries are Žerovniščica and Šteberščica, while on the southern side the larger springs are Laški Studenec, Tresenec, Retje, Otoški Obrh, Mrzlek, Vranja Jama v Zadnjem Kraju, Skadulca and the spring in Ušiva Loka. The Cerkniščica River is the only longer, non-karstic tributary of the lake, that receives water from the edge of the Otavska, Vidovska and Bloke plateaus (Kranjc, 1986). The outflow of Cerknica Lake consists of several outflow units and is entirely karstic. The most important ponors are connected to the Velika and Mala Karlovica cave system and the Svinjska Jama cave in the northwestern part of the polje, the so-called Jamski zaliv (Cave bay), which drain water mainly towards Rakov Škocjan and Planinsko Polje (Gams, 1965; Petrič et al., 2020). In the central part of the polje, there are numerous sinkholes (e.g. Rešeto and Vodonos south of the village of Dolenje Jezero), from which water flows underground directly into the springs of the Ljubljanica River (Gams, 1965). The lake water is retained the longest in the lowest part of the polje, the so-called Zadnji kraj, from where it also flows into the springs of the Ljubljanica (Gams, 1965; Kranjc, 1986).

Cerknica Lake begins to apear when the inflow exceeds the outflow and the water level rises above 547.4 m (184 cm at the Dolenje Jezero water gauging station) (Kolbezen, 1998). According to more recent studies, however, the regular lake level, defined as the water level that is exceeded on at least 10 days per year within a reference period of 30 years, is 550.3 m (value of 474 cm at the Dolenje Jezero gauging station). At this value, the water floods an area of 21.84 km^2 (Ravbar et al., 2021). The lake carries water for an average of nine months a year. The lake is most often full in April, May and December and empty between August and October (Kranjc, 2005). The water regime of the lake in the reference period 1961–1990 was characterised by two highs (April and December) and two lows (August and February) (Kovačič, 2010). According to the author's interpretation, the peak in April was partly due to snowmelt that had accumulated in the higher parts of the catchment during the winter and partly due to precipitation in the period preceding the intensive growing season. The peak in December was caused by a combination of the precipitation peak in November and a karst retention that shifted most of the November runoff from the polje to December. The low in August was due to heavy evaporation, while the low in February was due to snow retention. The attached graph (Figure 3) shows that the water regime of the lake changed in the following 30-year period (1991–2020) at the expense of significantly lower water levels in spring and summer and slightly higher water levels in fall. For the period 1961–2007, the lake's water regime was analysed for five decades by Zhelezov et al. (2011) and showed significant differences between the various decades.

Cerknica Polje is located in the municipality of Cerknica. The settlements in Cerknica Polje, with the exception of the central settlement of Cerknica, are predominantly rural. With the exception of Dolenje Jezero, they have withdrawn from the area of influence of the floods (Smrekar, 2005). In 2020, they had a population of 6120 inhabitants, of which about 2/3 lived in Cerknica (SURS, 2022). Smaller settlements in the municipality have been characterised by a decline in population over the last 50 years, while larger settlements with better opportunities for the development of various activities (Cerknica, Unec, Rakek, Martinjak and Grahovo) have seen an increase in population. The majority of the working population is still employed outside the municipality (Pustovrh Benda, 2015). Cerknica Lake represents the tourist potential of the wider area, which is only partially exploited. Tourist arrivals are increasing, but these are mainly day-trippers who visit the lake mainly in the warmer season (Lukan, 2017).

Figure 3: Hydrograph of mean monthly water levels at the Dolenje Jezero water gauging station for the periods 1961–1990 and 1991–2020.



Source of the data: ARSO, 2022.

3 ANTHROPOGENIC INTERVENTIONS IN THE DRAINAGE REGIME OF CERKNICA LAKE

The periodic occurrence of Cerknica Lake has been regulated in various ways in the past, depending on the historical situation and the interests that gave rise to the initiatives. In the agricultural era, there was the idea of draining the lake or reducing the volume and duration of flooding in favor of arable land, while later there was a tendency to permanently dam the lake in order to develop tourism, fishing and electricity generation (Bidovec, 2007).

In the name of drainage, some of the sinkholes were lowered and cleaned until the Second World War, Velika Karlovica (Fig. 4) and Mala Karlovica, Rakovski Mostek, Svinjska Jama cave, Kamnje and Narte ponors were widened and deepened, some siphons were blasted, underground channels were widened and lowered and screens were installed at the entrance to both Karlovicas, the inflow to Svinjska Jama cave was regulated, Stržen with some tributaries was regulated and its outflow into the nearby sinkholes and ponors was regulated by drainage ditches. These measures have limited major flooding and led to a faster discharge of medium-high water (Kranjc, 1986).

Figure 4: Velika Karlovica (photo: S. Miklič).

Figure 5: Dam in front of Rešeto (photo: T. Trobec).

To prevent a catastrophic fish kill when the lake dried up, the locals built a small dam in front of Rešeto in 1946 (Figure 5), which prevented the low water from flowing into Rešeto sinkhole. They also built the Brkinov Laz dam on Stržen at a height of 200 cm at the Dolenje Jezero water gauging station to stem the flow of water towards Jamski Zaliv. In order to maintain the lowest water level, in 1956, in addition to the reconstruction of the dam in front of Rešeto (which was rebuilt and raised in 1969), part of Stržen and Žerovniščica were regulated and several small reservoirs were built at Ponikva, Retje and Sitarica (Kebe, 2011).

At the end of the 1960s, the entrance to the Mala Karlovica was concreted to test the damming of ponors, five cave entrances were built in Narti and the Velika Karlovica was dammed with a concrete dam with an overflow at 551 m (544 cm at the Dolenje Jezero water gauging station), and connected by an artificial tunnel to the Rakovski Mostek (Nova Karlovica), where an iron sluice was installed at the entrance. In this way, the outflow at medium and high water levels was reduced and floods were prolonged, but the lake continued to dissapear in periods of drought (Bidovec, 2007; Habič, 1974; Kranjc, 1986).

In the following years, the barrier in front of Velika Karlovica was lowered, some of the ponors were relieved and the cleaning and dredging of some channels was resumed. In the late 1980s and early 1990s, the Nova Karlovica facility was rebuilt and became the main sink for the outflow of water from Cerknica Lake, with a capacity of around 40 m^3/s (Pravilnik za obratovanje …, 2014). In 1992, the concrete barrier at the entrance to Mala Karlovica was removed and after the floods of 2000, the overflow of the barrier at Velika Karlovica was lowered by 60 cm, so that water only flows over the barrier when the water level at the Dolenje Jezero water gauging station reaches 500 cm (Kebe, 2011).

In 2015, the implementation of a regulation prescribing the operating regime of the lock at Nova Karlovica began in order to protect the fish fauna, which is tied to high winter and spring water levels during spawning. The lock is closed on December 1st and remains closed until the middle or end of May (depending on the water level). It is only opened when the water level at the Dolenje Jezero gauging station exceeds 470 cm, and even then only until the water level stops rising (Pravilnik za obratovanje …, 2014). The lock in Nova Karlovica was not operated before 2015, but it is assumed that it was open most of the time and was cleaned regularly (Tratnik, 2023).

In 2016 and 2018, the fishing weir in Rešeto was rebuilt and upgraded with an overflow height of 150 cm at the Dolenje Jezero water gauging station (Tratnik, 2023), which keeps the water in the lake at an approximate height of about 70 cm at the Dolenje Jezero water gauging station during low water levels (Schein, 2020).

Between 2019 and 2021, under the management of the Notranjska Regional Park, the original channel of the Stržen in Ključi and Beli Breg was restored and in 2009 the upper parts of Goriški Brežiček and Tresenec were renaturated, which is expected to slightly slow down the outflow of low water and prolong the stagnation of water in the depressions and established arms of the watercourses (Tratnik, 2023).

4 METHODS

For the study area, we analysed the mean annual and seasonal precipitation, snow cover and total snow depth, mean annual and seasonal air temperature, mean annual and seasonal minimum (Hnp), mean (Hs) and maximum (Hvp) water level of Cerknica Lake, and minimum (Qnp), mean (Qs) and maximum (Qvk) annual discharge of the Cerkniščica River for the period 1961–2020. The seasonal values refer to the meteorological seasons, with the December–February quarter representing winter, the March–May quarter representing spring, the June–August quarter representing summer and the September–November quarter representing fall.

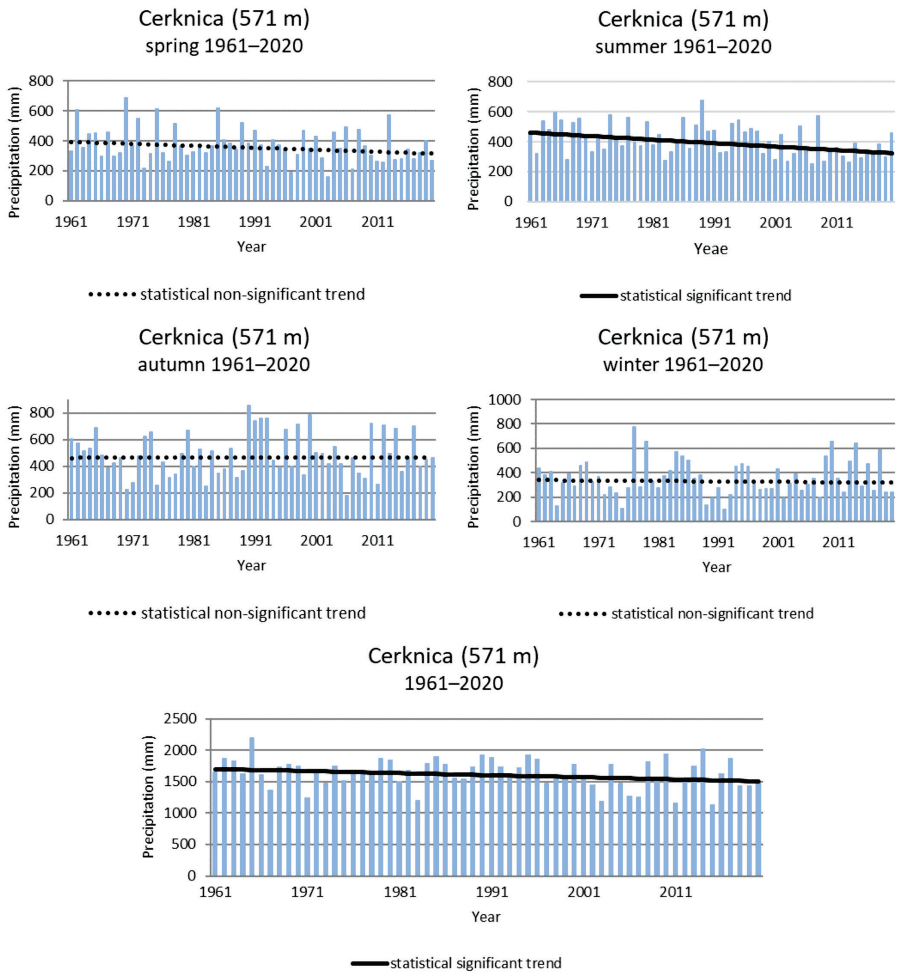
To calculate the trends in precipitation and snow cover in the study area, we used the monthly precipitation heights from the Cerknica precipitation station (ARSO, 2022), which has a complete set. According to this criterion, the Šmarata and Nova Vas na Blokah stations could also have been included in the analysis, but the preliminary analysis showed a high level of agreement in the trends and annual distribution of precipitation between the stations, which is why we ultimately decided against it. For the calculation and presentation of the trend of the average daily temperature, the temperature data from the climatological station Dolenje Jezero, which has only been in operation for less than ten years, were interpolated with the temperature data from the climatological station Postojna, which is the closest station with a homogenised data set. In the interpolation, we also calculated the difference in monthly mean air temperature for the entire period of operation of the stations (1969–1977) and then added the difference to the data set of the Postojna meteorological station for the period 1961–2020. In the study, we did not separately consider evapotranspiration, which is otherwise calculated for Bloke and Babno Polje, as it is a derived (calculated) and not a basic (measured) meteorological variable. For the analysis of the water levels of Cerknica Lake, we used the monthly data of minimum, mean and maximum water levels at the Dolenje Jezero gauging station, and for the analysis of the discharge of the Cerkniščica River, we used the monthly discharges at the Cerknica gauging station (ARSO, 2022).

The trend of temperature, precipitation and snow cover, water levels and discharges were calculated using the Mann-Kendall statistical test and Sen's slope. The Mann-Kendall test indicates the significance of the trend, if it exists, and the Sen's slope indicates the value. The Mann-Kendall test and Sen's slope were calculated in MS Excel using the MAKESENS template (Makesens-application ..., 2021). The correlation between the selected meteorological and hydrological variables was determined using the Spearman rank correlation coefficient (ρ), in which the data are converted into ranks before calculation and are therefore less sensitive to outliers. In contrast to the Pearson correlation coefficient, the Spearman correlation coefficient also assumes no linear correlation between the variables and a normal frequency distribution (Helsel et al., 2020) and is therefore more suitable for analysing the correlation between meteorological and hydrological variables, representing inputs and outputs of karst systems (Kovačič, 2009).

5 RESULTS

In the period 1961–2020, the average annual precipitation at the Cerknica precipitation station was 1629 mm. There is a negative trend, which is statistically significant ($\alpha \leq 5\%$), of –33 mm/decade, which means that precipitation decreased by 197 mm or 11% in the analysed period. The wettest year was 1965 with 2189 mm of precipitation and the driest year was 2015 with only 1125 mm of precipitation. With the exception of the fall, the seasonal trends in precipitation are also negative. The

Figure 6: Temporal course of average precipitation 1961–2020 at the Cerknica precipitation station.

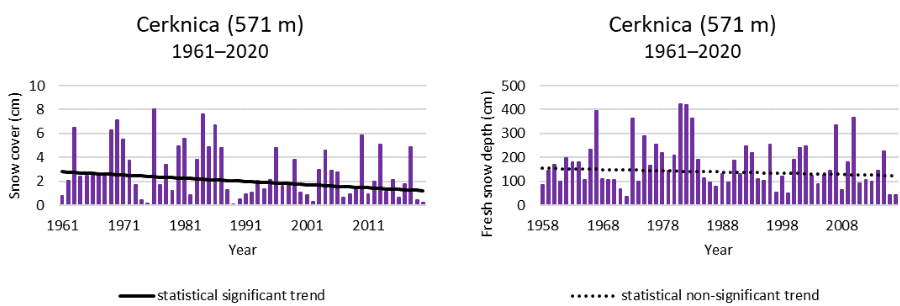


Source of the data: ARSO, 2022.

linear trend in spring is statistically insignificant at –13 mm/decade, which means that precipitation in spring has decreased by 79 mm or 20 %, while the average precipitation in spring during the analysed period was 373 mm. The average summer precipitation during the period studied was 413 mm. The decrease in summer precipitation is most pronounced compared to the other seasons, with a decrease of 30 % or 139 mm. The linear trend in summer is statistically significant (α ≤ 5%) and amounts to –23 mm/decade. The average amount of precipitation at the Cerknica precipitation station was highest in the fall at 488 mm during the study period. However, the linear trend in fall precipitation is insignificant and statistically insignificant at 0.4 mm/decade. Precipitation in the fall increased compared to the other seasons, but only by 0.5% or 2 mm. The average winter precipitation over the period studied was 356 mm, which indicates a primary decrease in winter precipitation. At –3 mm/decade, the trend is statistically insignificant. Winter precipitation therefore decreased by 21 mm or 6% (Figure 6).

Two variables were analysed for the snow depth 1961–2020 at the Cerknica precipitation station: the average snow cover and the total new snow depth (Figure 7). The average snow cover in a given period corresponds to the arithmetic mean of all daily values, even if there is no snow (snow cover is 0 cm), while the total snow depth is the sum of the daily values of new snow in the selected period (Vertačnik, Bertalanič, 2017). In the period studied, the highest average snow cover was in 1976 (8 cm) and the lowest in 1989 (0.1 cm). Until 1986, values above 6 cm occurred five more times (1963, 1969, 1970, 1984 and 1986), but no more after that. The highest total new snow depth was 421 cm in 1984 and the lowest in 1975 (35 cm). In 1970, 1976, 1985, 1986 and 2013, the value was over 350 cm.

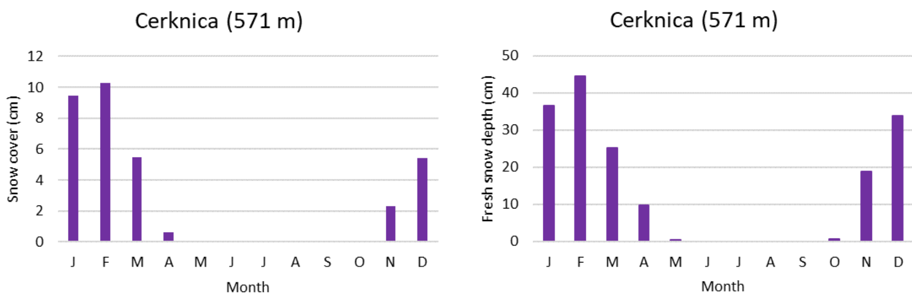
Figure 7: Temporal course of the average snow cover and new snow depth for the period 1961 – 2020 at the Cerknica precipitation station.



Source of the data: ARSO, 2022.

The snowiest month in the Cerknica Polje area during the study period was February (Figure 8). The average snow cover in February was 10.3 cm and the average total new snow depth was 45 cm. Most of the new snow (over 25 cm on a monthly basis) fell on average between December and March. The average annual snow depth was 2.8 cm and the total new snow depth was 170 cm. A statistically significant trend (α ≤ 5%) was observed for the average snow depth over the period studied, which amounted to –0.26 cm/decade, a decrease of 1.6 cm or 57%. For the total new snow depth, the trend is also negative (–5 cm/decade), but not statistically significant. On an annual basis, the amount of new snow fell by 31 cm or 20% in the period studied.

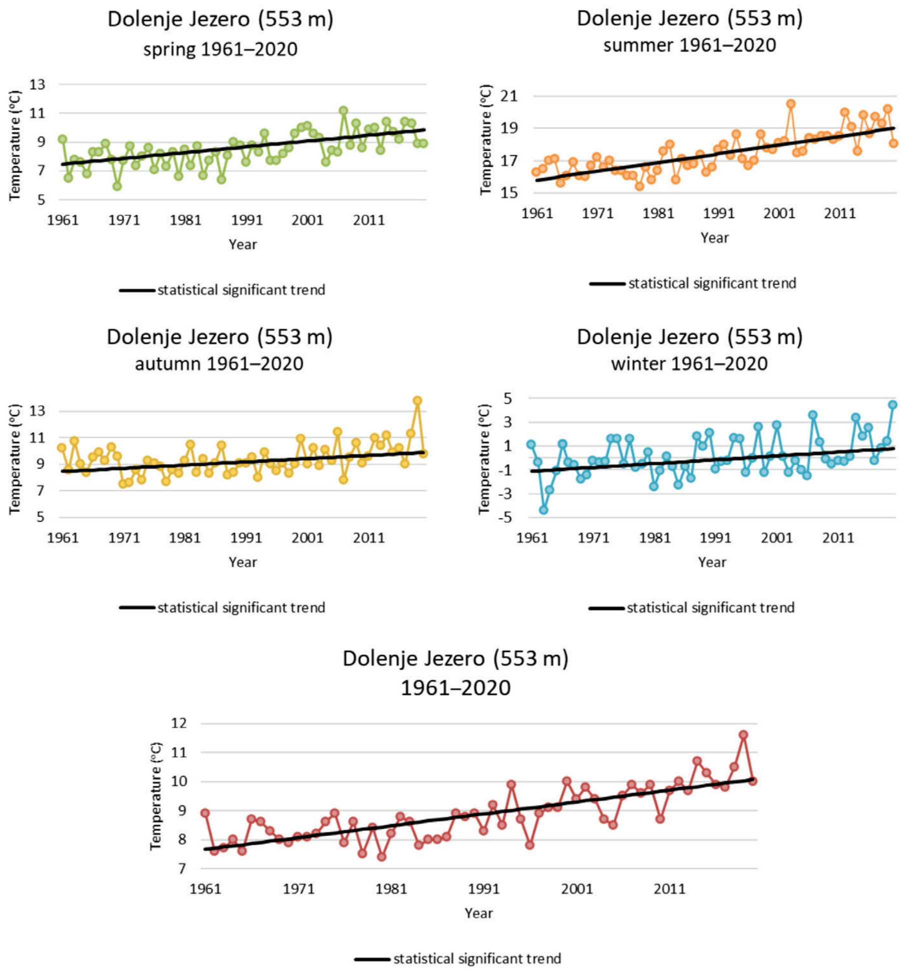
Figure 8: Monthly average amount of new snow and snow cover at the Cerknica precipitation station 1961–2020.



Source of the data: ARSO, 2022.

The average annual air temperature at the climatological station Dolenje Jezero in the period 1961–2020 was 8.9 °C. The lowest average annual air temperature was measured in 1980 with 7.4 °C, and the warmest year was 2019 with an average temperature of 11.6 °C. There is a positive and statistically significant trend (α ≤ 5%) of 0.4 °C/decade, which means that the atmosphere has warmed by 2.5 °C over the period studied. Unlike the trends in mean precipitation, the trends in mean air temperature are positive and statistically significant (α ≤ 5%) in all seasons. The warming rate is highest in summer, when the linear trend is 0.5 °C/decade. In spring, the linear trend of the mean air temperature is 0.4 °C/decade, in fall 0.2 °C/decade and in winter 0.3 °C/decade. In summer it warmed by an average of 3.2 °C, in fall by 1.5 °C, in winter by 1.9 °C and in spring by 2.3 °C (Figure 9).

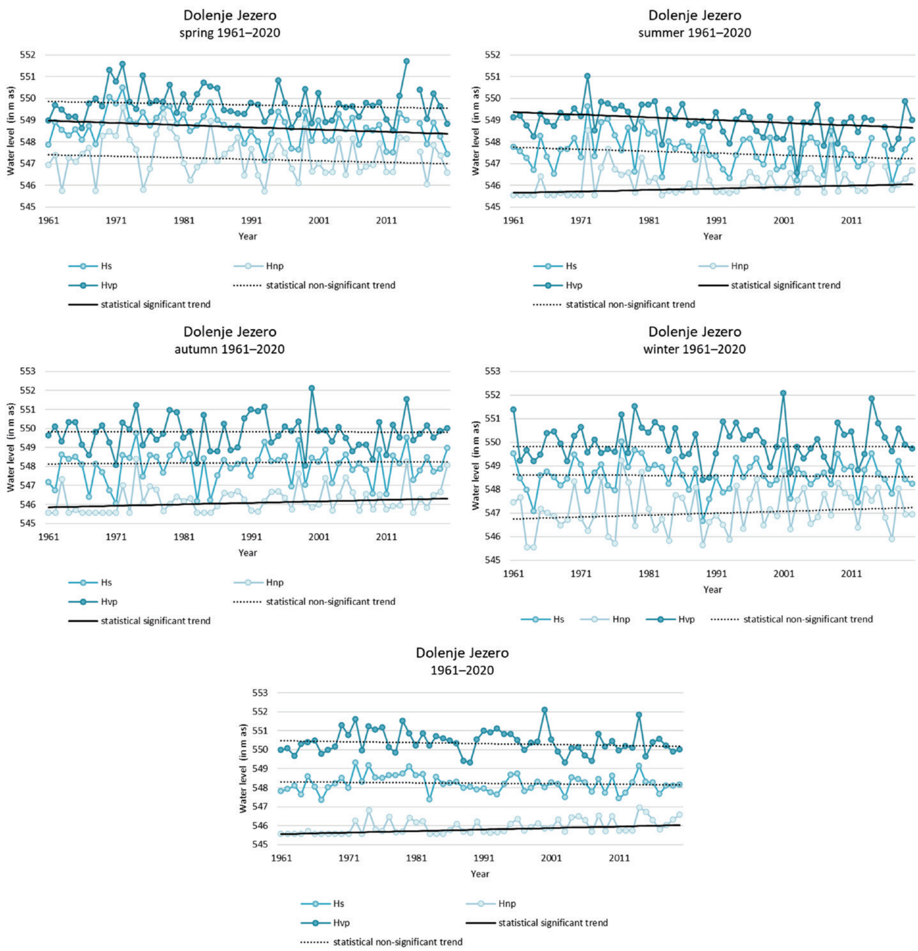
Figure 9: Temporal course of the average air temperature 1961 – 2020 at the Dolenje Jezero climatological station.



Source of the data: ARSO, 2022.

The different water levels (Hnp, Hs and Hvp) are subject to different trends and associated changes in their height both on an annual basis and at different times of the year during the study period (Figure 10, Figure 11). The trends of the highest (Hvp) and mean (Hs) annual water levels of Cerknica Lake at the Dolenje Jezero gauging station between 1961 and 2020 were negative and not statistically significant, while the trend of the lowest annual water levels (Hnp) was positive and statistically significant ($\alpha \leq 5\%$). According to the linear trend equation, Hvp decreased the most during the analysed period (30 cm). The decrease in Hs was 16 cm and the increase in Hnp was 48 cm. In spring, water level trends were negative, but only the trend for Hs was statistically significant (α ≤ 5%), with a decrease of 62 cm over the period studied, which was also the largest decrease among all seasonal Hs. In spring, Hnp decreased by 42 cm and Hvp by 32 cm. In summer, the trends of Hvp and Hs were negative, with the former also being statistically significant (α ≤ 5%), and the trend of Hnp was positive and also statistically significant (α ≤ 5%). In summer, the most significant decrease was 74 cm in Hvp (the largest decrease among all seasonal Hvp), while Hnp increased by 40 cm and

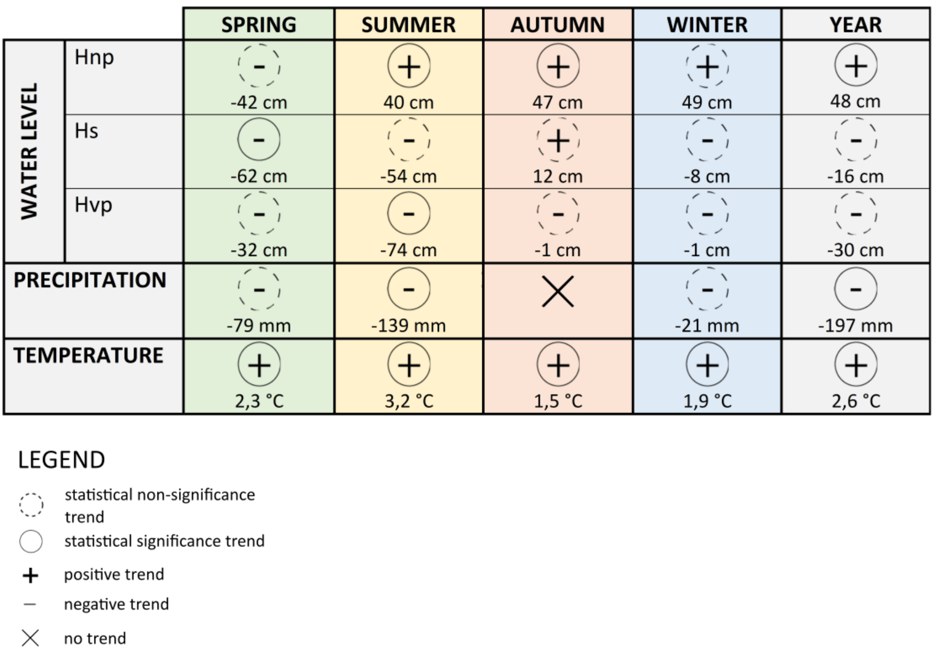
Figure 10: Temporal course of the lowest, average and highest water levels in the period 1961–2020 at the Dolenje Jezero water gauging station.



Source of the data: ARSO, 2022.

Hs decreased by 54 cm. In the fall, the linear trend of Hs was negative and statistically insignificant with a decrease of 12 cm over the period studied, while the trend for Hvp was insignificant. The fall trend for Hnp was positive and statistically significant (α ≤ 5%), with a 47 cm increase in summer minimum water levels. In winter, the trends for Hvp and Hs were negative and not statistically significant, while the trend for Hnp was positive and also not statistically significant. The largest change was for Hnp (increase of 49 cm), Hs decreased by 8 cm and Hvp remained practically the same.

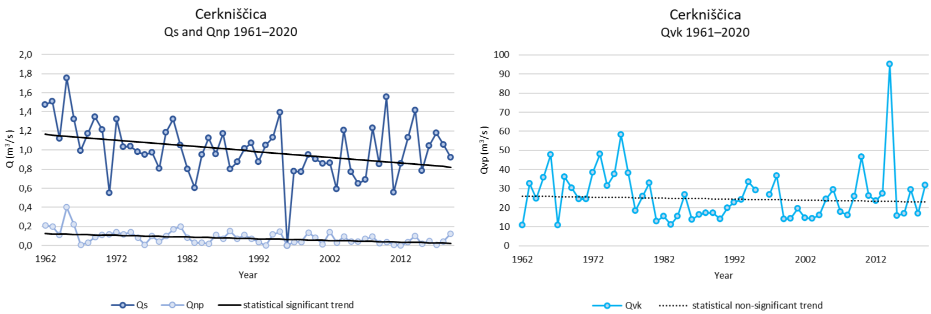
Figure 11: Synthesis of trends of selected meteorological variables and water levels in the period 1961–2020 for the precipitation station Cerknica and the climatological and water gauging station Dolenje Jezero.



Source of the data: ARSO, 2022.

The trends of annual discharges on the Cerkniščica River were negative in the period 1961–2020. The trends of Qnp and Qs are statistically significant (α ≤ 5%), while the trend of annual Qvk is not statistically significant. The decrease in Qs over the period studied was 0.32 m^3/s (28%), the decrease in Qvk was 3.17 m^3/s (12%) and the decrease in Qnp was 0.09 m^3/s or 78% (Figure 12).

Figure 12: Temporal course of Qnp, Qs and Qvp in the period 1961–2020 at the Cerknica water gauging station.



Source of the data: ARSO, 2022.

The correlation between the water levels and the selected meteorological variables was determined using Spearman's rank correlation coefficient (ρ) (Table 1). The correlation between the different water levels (Hnp, Hs, Hvp) and air temperature is low in most cases (ρ between ±0.20 and ±0.39), in some cases even insignificant (ρ between ±0.01 and ±0.19) and has a different sign at different times of the year. The largest negative correlation (mean) is between Hs and Hvp in summer with air temperature (ρ = –0.48 and –0.49, respectively), and there is another mean correlation between Hnp in summer and air temperature, but it is positive (ρ = 0.41). The correlations of annual water levels with air temperature vary considerably in absolute value and also have different signs (–0.30 < ρ < 0.41). In spring and summer, the correlations are negative and insignificant to medium (–0.03 < ρ < –0.49), in winter positive and insignificant to low (–0.19 < ρ < 0.24) and in fall insignificant and with a different sign (–0.07 < ρ < 0.08).

The correlation between the different water levels (Hnp, Hs, Hvp) and precipitation is positive everywhere and on average higher than the correlation between water level and air temperature. In slightly more than half of the cases, it is at least medium (ρ between 0.40 and 0.59), of which two cases are high (ρ between 0.60 and 0.79) and one case is very high (ρ > 0.80). The highest correlation between Hvp and precipitation is in fall (ρ = 0.86). There is a medium correlation between annual Hvp and precipitation (ρ = 0.52) and a low correlation (ρ = 0.39) and an insignificant correlation (ρ = 0.01) between annual Hs and Hnp and precipitation. With the exception of the annual level and fall, the most pronounced correlation between all water levels is that between annual Hvp and precipitation. Hs and precipitation are most strongly correlated. In spring and summer it is medium (ρ = 0.55 and 0.46 respectively) and in fall and winter it is high (ρ = 0.64 and 0.63 respectively). There is only a low correlation between the annual and autumnal Hnp and the amount of precipitation (ρ = 0.01 and 0.08 respectively).

Table 1: Values of Spearman's rank correlation coefficient (ρ) between water levels and air temperature and precipitation.

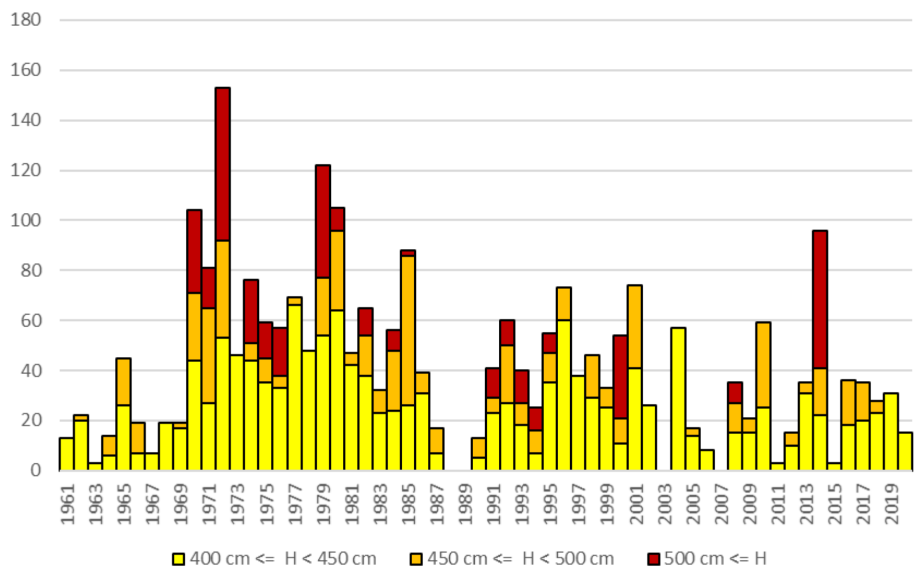
	Air temperature	Precipitation
Annual Hs	–0,30*	0,39*
Annual Hnp	0,41*	0,01
Annual Hvp	–0,17	0,52*
Spring Hs	–0,40*	0,55*
Spring Hnp	–0,33*	0,39*
Spring Hvp	–0,19	0,45*
Summer Hs	–0,48*	0,46*
Summer Hnp	–0,03	0,24*
Summer Hvp	–0,49*	0,38*
Fall Hs	–0,07	0,64*
Fall Hnp	0,08	0,08
Fall Hvp	–0,05	0,86*
Winter Hs	0,19	0,63*
Winter Hnp	0,24*	0,40*
Winter Hvp	0,21	0,46*

**The correlation is statistically significant (α ≤ 5%).*

6 DISCUSSION

The negative trend in mean and maximum water levels and thus the decrease in annual Hs (16 cm) and Hvp (0.30 cm) of Cerknica Lake in the period 1961–2020 is probably mainly due to a decrease in annual precipitation by 11% and an increase in mean air temperature by 2.5 °C, with a consequent increase in evaporation. The latter hypothesis is indirectly supported by the relationships of water levels to precipitation and temperature, namely the small correlation between Hs and precipitation (ρ = 0.39), the medium correlation between Hvp and precipitation (ρ = 0.52) and the small and insignificant negative correlation of Hs and Hvp to air temperature (ρ = –0.30 and –0.17, respectively). Part of the decline in mean water levels and peak water levels could also be related to the gradual removal of some measures taken in the late 1960s to implement the experimental impoundment (Kranjc, 1986), such as the release of some ponors, the removal of the barrier at the entrance to Mala Karlovica, the lowering of the overflow of the barrier at Velika Karlovica and the resumption of clearing and dredging of some of the river channels (Kebe, 2011). Despite the negative trend in Hvp, it is worth noting that the absolute highest water levels were reached in the second half of the study period, namely in 2000 (654 cm) and 2014 (628 cm), when floods occurred in a larger area of Slovenia (ARSO, 2014; Kovačič, Ravbar, 2010). Blatnik et al. (2024), who in contrast to us look at a somewhat longer data set (1956–2022), find a slightly positive trend in Hvp. The divergence is due to the high variability of annual maximum water levels, where even small differences in the investigated set can influence the reversal of the trend. The extreme water levels in 2000 and 2014 are consistent with the findings of more frequent and more pronounced flooding as a result of climate change (Kobold, Dolinar, Frantar, 2012) and indicate that there is a real possibility that we will experience more frequent extreme flooding at Cerknica Lake in the future, regardless of the trend in Hvp, when exceptional precipitation occurs. In general, however, the number of days with the highest water levels, e.g. above 400, 450 or 500 cm, is decreasing at Cerknica Lake, even if we exclude the period of attempted permanent management of the lake in the transition from the 1960s to the 1970s (Figure 13).

Figure 13: Number of days per year with high water levels at the Dolenje Jezero gauging station in the period 1961–2020.

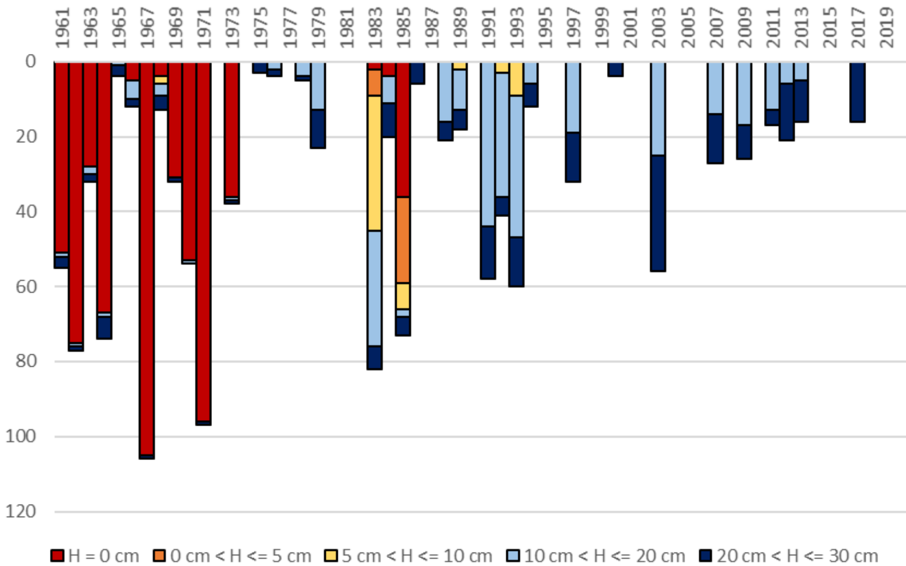


Source of the data: ARSO, 2022.

In contrast to Hs and Hvp, the trend of Hnp is positive and statistically significant ($\alpha \leq 5\%$), leading to an increase in the lowest annual water levels (increase of 48 cm). There is a lack of correlation of annual Hnp with rainfall ($\rho = 0.01$) and a moderate correlation with air temperature ($\rho = 0.41$), with the latter having the opposite sign to that expected. The increase in annual minimum water levels despite lower precipitation and higher temperature is probably due to anthropogenic interventions in outflow. In this case, the dam at Rešeto sinkhole, behind which water is held back at low water levels to protect fish, has a decisive influence. In fact, all annual Hnp recorded during the studied period were below the overflow of the dam (150 cm at the Dolenje Jezero water gauging station). However, the dam was damaged, rebuilt and raised several times during the study period to retain more water (Schein, 2020; Tratnik, 2023), which could explain the increasing trend in Hnp. However, water retention at the lowest water levels is probably not the only reason for the increase in Hnp. We suspect that the latter phenomenon is partly due to the way water levels are measured, which is unfavourable for studying the lowest values at the Dolenje Jezero gauging station. A look at the attached graph (Figure 14) shows that from the beginning of the station's operation until 1974, values of H = 0 cm (absolute height 545.56 m) were recorded very frequently, which is no longer typical for the later period (with some exceptions in the early 1980s). Since 1974, water levels of less than e.g. 5, 10, 20 or 30 cm have also become increasingly rare, although it is known from experience that the Stržen River can dry out during dry periods. For example, in the exceptionally dry year of 2022, despite the absence of water, the lowest water level was officially recorded at H = 30 cm (ARSO, 2022) because the water level bar with the value 0 cm was buried in the sediment at the bottom of the channel at the time of measurement (Figure 15). In view of the many recorded values of H = 0 cm at the beginning of the study period, it is possible that the bed of the channel was deeper at this time and the water level bar at 0 cm was therefore not buried in the sediment. It is also quite possible that before 1974 (when continuous recording of water levels with a limnigraph was introduced) the observer recorded the water level at H = 0 cm when there was no water in the channel, regardless of whether the water level gauge was buried in the sediment at 0 cm, which was no longer possible due to automatic recording in the later period. There are no official record of how the lowest water levels were recorded until 1974 and of the burial of the level at 0 cm in the sediment, so the trend in annual Hnp is unlikely to be reliably interpreted.

The discharge data for the only larger non-karstic tributary of the Cerknica polje – the Cerkniščica – at the Cerknica gauging station show, according to the linear trend equation, a decrease in mean annual discharge (Qs) and annual peak discharge (Qvk) by 28% and 12% respectively in the same period (1961–2020), which is consistent with the changes in Hs and Hvp of the Stržen at the Dolenje Jezero gauging station. In contrast to the increase in Hnp in the analysed period, the annual minimum discharge (Qnp) at Cerknica decreased by 78%. The latter fact is further indirect evidence that the increase in minimum water levels at Cerknica cannot be climatic, but is due to another factor – most likely an anthropogenic influence on the outflow.

Figure 14: Number of days with low water levels at the Dolenje Jezero water gauging station in the period 1961–2020.



Source of the data: ARSO, 2022.

Spring Hs, Hnp and Hvp of Cerknica Lake decrease (62 cm, 42 cm, 32 cm decrease), which is consistent with decreasing spring precipitation (20% decrease) and increasing temperatures (2.3 °C increase) affecting evaporation. The latter is also reflected in a medium correlation between Hs, Hnp and Hvp in spring with precipitation ($0.39 < \rho < 0.55$) and a small negative correlation with temperature ($-0.40 < \rho < -0.19$). The significant decline in water levels in spring also becomes clear when comparing the mean water levels in March, April and May for the periods 1961–1990 and 1991–2020 (Figure 3). The decline in water levels in spring is probably partly due to the reduced influence of snow retention. This is a combination of a lower proportion of snowfall in winter, which only partially runs off in spring, and less abundant winter precipitation (a 6% decrease). The lower proportion of snowfall is reflected in a 20% decrease in the amount of new snow, while the 57% decrease in average snowpack height indicates faster snowmelt, which consequently turns into runoff with a shorter time lag. The latter results are consistent with those on snowpack depth in Slovenia, which decreased by about 16% per decade at the national level between 1961 and 2011 (Vertačnik, Bertalanič, 2017), and the weakening of snow retention is reflected in a reduction of spring discharge in many watercourses (Frantar, Hrvatin, 2005). When assessing the impact of snowfall on the water level of Cerknica Lake, it should be noted that the analyses were carried out at the lowland precipitation station Cerknica, which is not representative of the entire catchment area of Cerknica Lake due to the lack of precipitation stations at higher altitudes, as snow only occurs in larger quantities at higher altitudes.

Figure 15: Dry riverbed of the Stržen in summer 2022 (photo: T. Trobec).

Summer Hs declined by 54 cm during the period studied, the second largest decline in Hs after spring, and summer Hvp declined by 74 cm, the largest decline among seasonal Hvp. The significant decline in summer water levels is also evident when comparing the mean water levels of June, July and August for the periods 1961–1990 and 1991–2020 (Figure 3). This decrease in summer Hvp and Hs can probably be attributed to the increased evaporation due to the warming of the atmosphere (the summer temperature increase of 3.2 °C is the highest of all seasons) and to the significant decrease in precipitation, which is most pronounced in summer (30%). This hypothesis is also supported by the mean correlation of Hs and Hvp in summer with precipitation ($\rho = 0.46$ and 0.38, respectively) and with air temperature ($\rho = -0.48$ and –0.49, respectively), which has the expected negative sign at this time of year. Despite the strong decrease in summer precipitation and warmer temperatures, the trend of summer Hnp is positive (increase of 40 cm) and the trend of autumn Hnp is very similar (increase of 47 cm). Considering that 87% of Hnp on an annual basis occurs in summer or autumn (and occasionally in both seasons simultaneously) during the studied period, the interpretation of the trend in summer and autumn Hnp is also unreliable (as in annual Hnp) due to the above-mentioned methodological uncertainties in the recording of minimum water levels. However, as mentioned above, the positive trend in summer and autumn Hnp can probably be linked, at least in part, to artificial water retention at low water levels behind the dam at Rešeto. Indeed, the vast majority of summer and autumn Hnp (90% and 88%, respectively) in individual years at the Dolenje Jezero gauge were below 150 cm, which corresponds to the overflow height of the dam. The hypothesis of the influence of artificial water retention on the lowest summer and autumn water levels is also indirectly confirmed by the insignificant and low correlation of summer and autumn Hnp with precipitation ($\rho = 0.24$ and 0.08, respectively) and the insignificant correlation with air temperature ($\rho = -0.03$ and 0.08, respectively), which is also inverse to that expected in autumn. According to the linear trend, the autumn changes in Hs were relatively small (12 cm increase) during the studied period, while Hvp remained practically the same. The small changes in water levels are probably due to the insignificant changes in autumn precipitation (0.5% increase) and the relatively modest increase in autumn temperatures (1.5 °C increase; the smallest of all seasons). This is indirectly supported by the high to very high correlation of Hs and Hvp in fall with precipitation ($\rho = 0.64$ and 0.86, respectively), while the correlation with temperature is insignificant.

In winter, the trend in water levels is similar to that in autumn, with Hnp rising in winter (49 cm) and Hs and Hvp experiencing no major changes. Hs has fallen slightly (8 cm), while Hvp has remained practically the same. The small change in the average water level in winter is also illustrated by the almost identical values of the average water levels in December, January and February at the Dolenje Jezero gauging station when comparing the periods 1961–1990 and 1991–2020 (Figure 3). The small changes in water levels are probably due to the relatively small change in winter precipitation

(6% decrease), which is also reflected in the medium to high correlation of Hs and Hvp in winter with precipitation (ρ = 0.63 and 0.46, respectively). There was also a significant increase in winter temperature (1.9 °C) over the period studied, but due to the otherwise low temperatures at this time of year, this has no significant effect on the increased evaporation and thus the lower runoff. The latter is also reflected in the correlation of winter Hnp, Hs and Hvp with temperature ($0.19 < \rho < 0.23$), which has a positive sign. Hs in winter remains at a similar level, possibly because the decrease in winter precipitation is compensated to some extent by faster runoff. This is a result of the already mentioned weaker effect of snow retention (less snowfall in winter and faster melting and runoff of newly fallen snow due to warmer temperatures). The reduced effect of snow retention is probably also the cause of the increase in winter Hnp.

Above is a vertical overview of the changes in the analysed meteorological and hydrological variables by season and below a horizontal overview of the changes in the individual water levels (Hnp, Hs, Hvp) of Cerknica Lake over the course of the year. The mean water level (Hs) has decreased in the period 1961–2020 both on an annual and seasonal level (with the exception of autumn, when a slight increase is recorded), and its changes coincide with lower precipitation, higher temperatures and higher evaporation. The decline in Hs is greatest in spring and summer, when changes in precipitation and temperature are also greatest. The maximum water levels (Hvp) also show a decline (except in winter and autumn, where there were practically no changes). Here too, the decline was greatest in spring and summer due to lower precipitation and higher temperatures. The decline in Hs and Hvp in spring and summer could also be related, at least to a small extent, to the aforementioned phasing out of some experimental damming measures in the late 1960s (Kebe, 2011; Kranjc, 1986). The lowest water levels (Hnp), on the other hand, are characterised by an increase (except in spring) that contrasts with the observed changes in precipitation and temperature. The increase in Hnp on an annual basis and in summer and autumn, when water levels are generally lowest, can be explained (as far as the above-mentioned questionable methodology for recording the lowest water levels allows) by the artificial water retention at low water levels behind the dam at Rešeto (Schein, 2020; Tratnik, 2023). However, the Hnp in winter and spring are generally higher than the Hnp in summer and autumn and exceed 150 cm at the Dolenje Jezero gauging station in about half of the years of the study period, which means that the water retention behind the dam at Rešeto has a relatively smaller influence on them than in summer and autumn. In a good third of cases, they also exceed 200 cm, when the water of Cerknica Lake begins to overflow in large quantities over the dam of Brkinov Laz towards Jamski Zaliv (Habič, 1974; Tratnik, 2023), and thus a significant part of the water in Karlovica and in many other ponors and sinkholes downstream of Rešeto begins to sink. Given the similar distribution of winter and spring Hnp occurrence in relation to the overflow heights of the dam at Rešeto and the Brkinov Laz dam, we conclude that the effects of anthropogenic interventions on Hnp are similar in both seasons and that the reason for this different trend is probably largely due to climate change. The increase in Hnp in winter (49 cm) and the simultaneous decrease in Hnp in spring (42 cm) may be due to the aforementioned weakening effect of snow retention. Although the additional winter inflow to the lake from this source has no influence on the increase in Hnp in winter, it may nevertheless influence the increase in minimum water levels in the complex karst recharge system of Cerknica Lake. However, the lack of spring inflow to the lake due to the reduced influence of snow retention is probably only an additional factor for the already abundant decrease in water levels in spring (as a result of the above-mentioned lower precipitation and higher temperatures), which is also reflected in the summer Hnp.

The correlation between annual and seasonal water levels (Hnp, Hs and Hvp) and precipitation or air temperature is generally relatively low, especially for temperature, where the sign of the correlation is also inconsistent between years and between different water levels. In one third of the cases (10) at least a medium correlation ($0.40 < \rho < 0.59$) is reported, in two cases a high correlation ($0.60 < \rho < 0.79$) and in only one case a very high correlation ($\rho > 0.80$). The lower correlation is probably influenced by several factors, both natural and anthropogenic. One of them is certainly the karst retention effect, which causes the water level of Cerknica Lake to react to precipitation with a certain delay and the water level in the lake remains high for a long time after precipitation. Blatnik et al. (2024), for example, found the highest correlation between the daily water level of Cerknica Lake and the sum of the preceding 45 days of effective precipitation (precipitation minus evapotranspiration) for the period 1954–2022. The second reason is methodological, as we used actual and not effective precipitation in the present study. The third reason is the numerous anthropogenic interventions in outflow, which had different effects at different times at different water levels (Blatnik et al., 2024; Habič, 1974). The higher correlation between water levels (Hnp, Hs and Hvp) and precipitation compared to the correlation between water levels and air temperature, both on an annual and seasonal basis, indicates a generally higher influence of precipitation on lake water levels. The slightly stronger negative correlation between water level and air temperature (which is still lower than the correlation between water level and precipitation) is only observed in spring and summer and indicates a stronger influence of temperature on water levels, especially in the warmer season when evaporation is also more intense during the growing season.

7 CONCLUSION

Climate change affects the discharge regime of watercourses and the water levels of lakes. We selected the intermittent Cerknica Lake to study the effects of climate change because its karstic nature makes it even more susceptible to any kind of change (including climate change). In this paper, we investigated the annual and seasonal changes in the water level of Cerknica Lake between 1961 and 2020 and tried to find correlations with local climate change. To this end, we analysed the annual and seasonal changes in precipitation, snow cover and air temperature, the changes in minimum (Hnp), mean (Hs) and maximum (Hvp) water levels of Cerknica Lake, and the trends in minimum (Qnp), mean (Qs) and maximum (Qvk) discharges of the Cerkniščica River in the area of Cerknica polje and its immediate catchment.

The analyses of meteorological and hydrological variables indicate a significant change in the water balance of Cerknica Lake during the period under study. The amount of precipitation in the area of Cerknica polje decreased by 11% or almost 200 mm. The decrease was most pronounced in summer (30%) and spring (20%). The amount of new snow fell by 20% and the average snow cover by 57%. The air temperature rose by 2.5 °C. It warmed the most in summer (3.2 °C) and spring (2.3 °C). Cerknica Lake has received less and less water over the years, which is reflected in a 16 cm decrease in the average annual water level (Hs). According to the linear trend equation, the maximum water level (Hvp) has fallen by 30 cm and the minimum water level (Hnp) has risen by 48 cm. The decrease in Hs and Hvp is mainly related to lower precipitation and higher air temperatures, which have led to an increase in evaporation, and to a lesser extent perhaps also to the phasing out of some anthropogenic water retention measures from the late 1960s, which at that time reduced runoff during mean and high water and led to prolonged flooding. However, the increase in Hnp (as far as the unreliability of the data at low water levels allows) can probably be linked to the artificial retention of water in the lake behind the repeatedly rebuilt and raised dam at Rešeto at low water levels, which is intended to preserve fish populations.

In spring, Hs, Hnp and Hvp of Cerknica Lake decreased significantly (62 cm, 42 cm, 32 cm). In summer, Hvp (74 cm) and Hs (54 cm) decreased and Hnp increased by 40 cm. In the fall, changes were limited to a 47 cm increase in Hnp, while changes in Hs were relatively small (12 cm increase) and Hvp remained virtually the same. In winter, Hnp also rose by 49 cm, while Hs and Hvp remained almost unchanged. The seasonal changes in the water level of Cerknica Lake in the case of Hs and Hvp, which decrease mainly in spring and summer, can be attributed to a considerable extent to the higher seasonal temperatures and increased evaporation as well as to the lower seasonal precipitation and partly perhaps also to the aforementioned phasing out of some of the anthropogenic high and medium water retention measures of the late 1960s. The lowest water levels (Hnp) show a seasonal increase (except in spring) that is similar to the annual increase, which contrasts with the observed changes in precipitation and temperature. The increase in Hnp in summer and autumn (which are usually also the lowest water levels of the year) can be linked to the artificial retention of water behind the Rešeto dam during the lowest water levels (as far as the unreliability of the data at the lowest water levels allows), as with the annual Hnp. However, the changes in Hnp in winter and spring (which are significantly higher than Hnp in summer and autumn and therefore less dependent on water retention at low water levels) can probably be linked to climate change and the associated decrease in snow retention.

Despite the relatively low correlation of annual and seasonal Hnp, Hs and Hvp with precipitation and air temperature, where at most one third of the relationships show at least a medium correlation ($0.40 < \rho < 0.59$), it can be concluded that climate change has a decisive influence on the changes in water level in the lake – especially for the mean water levels (Hs) and the maximum water levels (Hvp). Low water levels (Hnp) are more likely to be caused by anthropogenic interventions in the outflow than by climate change. The latter have been numerous in the past, sometimes with the aim of accelerating outflow, other times to retain water in the lake. Their impact on water level is difficult to assess objectively due to their often contradictory effects, the alternation between wet and dry years and the intermittent nature of the lake itself.

References

Andjelov, M., Frantar, P., Pavlič, U., Rman, N., Souvent, P., 2021. Količinsko stanje podzemnih voda v Sloveniji. Ljubljana: ARSO.

ARSO [Agencija Republike Slovenije za okolje], 2014. Hidrološko poročilo o poplavah v dneh od 8. do 27. februarja 2014. URL: https://www.arso.gov.si/vode/poro%c4%8dila%20in%20publikacije/Porocilo%20poplave%208-27%20feb%202014%20splet.pdf (accessed 04.08.2022).

ARSO [Agencija Republike Slovenije za okolje], 2022. Meteorološki in hidrološki podatki. URL: https://www.arso.gov.si/ (accessed 16.08.2022)

Bertalanič, R. et al., 2018: Ocena podnebnih sprememb v Sloveniji do konca 21. stoletja. Sintezno poročilo – prvi del. Ljubljana: ARSO.

Bidovec, M., 2007. Pretekli posegi na Cerkniškem jezeru. Novice Notranjskega regijskega parka, 1, 2, pp. 2–7.

Blatnik, M., Gabrovšek, F., Ravbar, N., Frantar, P., Gill, L. W., 2024. Assessment of climatic and anthropogenic effects on flood dynamics in the Cerkniško Polje (SW Slovenia) based on a 70-year observation dataset. Journal of Hydrology: Regional Studies, 51 (*in press*).

Bonacci, O., 1987. Man's influence on the water regime in the karst terrains. V: Bonacci, O. (ed.). Karst hydrology: with special reference to the Dinaric karst. Berlin: Springer, pp. 150–173.

Bonacci, O., 2014. Ecohydrology of karst poljes and their vulnerability. V: Sackl P., Durst, R., Kotrošan, D., Stumberger, B. (ed.). Dinaric karst poljes – floods for life. Radolfzell: EuroNatur, pp. 25–37.

Frantar, P. (ed.), 2008. Vodna bilanca Slovenije 1971–2000. Ljubljana: Ministrstvo za okolje in prostor, Agencija Republike Slovenije za okolje.

Frantar, P., Hrvatin, M., 2005. Pretočni režimi v Sloveniji med letoma 1971 in 2000. Geografski vestnik, 77, 2, pp. 115–127.

Gaberščik, A., Grašič, M., Abram, D., Zelnik, I., 2020. Water level fluctuations and air temperatures affect common reed habitus and productivity in an intermittent wetland ecosystem. Water 2020, 12, 10, pp. 2806.

Gaberščik, A., Urbanc-Berčič, O., Kržič, N., Kosi, G., Brancelj, A., 2003. The intermittent Lake Cerknica: Various faces of the same ecosystem. Lakes & Reservoirs Research & Management, 8, 3–4, pp. 159–168.
Gams, I. 1965. Aperçu sur l'hydrologie du karst Slovene et sus communications souterraines. Naše jame, 7, 1–2, pp. 51–60.
Gams, I. 1974. Kras v Sloveniji v prostoru in času. Ljubljana: Založba ZRC, ZRC SAZU.
George, G. (ed.), 2010. The impact of climate change on European lakes. Dordrecht, New York: Springer.
Habič, P., 1974. Tesnenje požiralnikov in presihanje Cerkniškega jezera. Acta carsologica, 6, pp. 35–56.
Helsel, D. R., Hirsch, R. M., Ryberg, K. R., Archfield, S. A., Gilroy, E. J., 2020. Statistical methods in water resources. Reston: U.S. Geological Survey. DOI: 10.3133/tm4a3.
Hrvatin, M., Zorn, M., 2020. Climate and hydrological changes in Slovenia's mountain regions between 1961 and 2018. Economic- and Ecohistory 16, 1, pp. 201–218.
IPCC, 2022. Climate Change 2022: Impacts, adaptation, and vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.). Cambridge University Press (*in press*).
Kayastha, M. B., Ye, X., Huang, C., Xue, P., 2022. Future rise of the Great Lakes water levels under climate change. Journal of Hydrology, 612, B, pp. 128–205.
Kebe, J., 2011. Cerkniško jezero in ljudje ob njem. Koper: Ognjišče.
Kobold, M., Dolinar, M., Frantar, P., 2012. Spremembe vodnega režima zaradi podnebnih sprememb in drugih antropogenih vplivov. I. kongres o vodah Slovenije, pp. 7–22.
Kolbezen, M., 1998. Hidrografija. In: Gams, I., Vrišer, I. (ed.). Geografija Slovenije. Ljubljana: Slovenska matica, pp. 139–172.
Kolbezen, M., Pristov, J., 1998. Površinski vodotoki in vodna bilanca Slovenije. Ljubljana: Ministrstvo za okolje in prostor, Hidrometeorološki zavod Republike Slovenije.
Kovačič, G., 2009. Hidrologija kraškega izvira Malenščica in njegovega hidrografskega zaledja. Doctoral dissertation. Koper: Univerza na Primorskem, Fakulteta za humanistične študije.
Kovačič, G., 2010. An attempt towards an assessment of the Cerknica polje water balance. Acta carsologica, 39, 1, pp. 39–50.
Kovačič, G., 2016. Trendi pretokov rek jadranskega povodja v Sloveniji brez Posočja. Geografski vestnik, 88, 2, pp. 9–29.
Kovačič, G., Ravbar, N., 2010. Extreme hydrological events in karst areas of Slovenia, the case of the Unica River basin. Geodinamica Acta, 23, 1–3, pp. 89–100.
Kranjc, A., 1986. Cerkniško jezero in njegove poplave. Acta geographica, 25, pp. 75–123.

Kranjc, A., 2005. Kako nastaja in izginja Cerkniško jezero? »Jezero, ki izginja« – monografija o Cerkniškem jezeru. Kras: revija o Krasu in krasu, o ljudeh in njihovem ustvarjanju, 70, pp. 12–17.

Lenters, J. D., Kratz, T. K., Bowser, C. J., 2005. Effects of climate variability on lake evaporation: Results from a long-term energy budget study of Sparkling Lake, northern Wisconsin (USA), 308, 1–4, pp. 168–195.

Life Stržen. 2019. URL: http://life.notranjski-park.si/sl/ (accessed 14.10.2019).

Lukan, A., 2017. Razvoj turizma v okolici Cerkniškega jezera. Ljubljana: Ekonomska fakulteta. URL: http://www.cek.ef.uni-lj.si/vps_diplome/lukan744.pdf (accessed 15.09.2022).

Makesens-application for trend calculation. 2021. URL: https://en.ilmatieteenlaitos.fi/makesens (accessed 13.05.2021).

Mayaud, C., Gabrovšek, F., Blatnik, M., Kogovšek, B., Petrič, M., Ravbar, N., 2019. Understanding flooding in poljes: a modelling perspective. Journal of Hydrology, 575, pp. 874–889.

Miklič, S., 2021. Spreminjanje vodostaja Cerkniškega jezera v obdobju 1958–2019. Master's thesis. Oddelek za Geografijo, Filozofska fakulteta, Univerza v Ljubljani.

Morrissey, P., Nolan, P., McCormack, T., Johnston, P., Naughton, O., Bhatnagar, S., Gill, L., 2021. Impacts of climate change on groundwater flooding and ecohydrology in lowland karst. Hydrology and Earth System Sciences, 25, pp. 1923–1941. DOI: 10.5194/hess-25-1923-2021.

Občina Cerknica. URL: https://www.stat.si/obcine/sl/Municip/Index/18 (accessed 15.09.2022).

Ogrin, D., 1996. Podnebni tipi v Sloveniji. Geografski vestnik, 68, pp. 39–56.

Perko, D., Orožen Adamič, M. (eds.), 1998. Slovenija. Pokrajine in ljudje. Ljubljana: Mladinska knjiga.

Petrič, M., Ravbar, N., Gostinčar, P., Krsnik, P., Gacin, M., 2020. Vzpostavitev prosto dostopne GIS zbirke rezultatov sledenj toka podzemne vode in možnosti njene uporabe. Geologija, 63, 2, pp. 203–220.

Pravilnik za obratovanje in vzdrževanje zapornice Nova Karlovica na Cerkniškem polju. 2014. URL: https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&ved=2ahUKEwiRqeGSpNqCAxVXhP0HHSUPBswQFnoECBMQAQ&url=https%3A%2F%2Frdcerknica.si%2Fwp-content%2Fuploads%2F2021%2F12%2FPRAVILNIK-ZA-OBRATOVANJE-IN-VZDRZEVANJE--NOVA-KARLOVICA.pdf&usg=AOvVaw0Ru4c8SYzdPLsmEZSo9LwD&opi=89978449 (accessed 22.11.2022).

Pustovrh Benda, M., 2015. Prikaz stanja prostora za območje občine Cerknica. URL: https://cerknica.eobcina.si/files/other/acts/31/9528Prikaz%20stanja%20prostora%202.pdf (accessed 19.09.2022).

Ravbar, N., Mayaud., C., Blatnik, M., Petrič, M. 2021: Determination of inundation areas within karst poljes and intermittent lakes for the purposes of ephemeral flood mapping. Hydrogeology Journal, 29, pp. 213–228. DOI: 0.1007/s10040-020-02268-x.

Schein, T., 2020. Posegi na Cerkniškem jezeru (personal information, 8. 10. 2020). Cerknica.

Smrekar, A. 2000: Cerkniško polje kot primer poseljenega kraškega ranljivega območja. Geographica Slovenica, 33, 1, pp. 117–156.

Spearmanov koeficient korelacije. URL: https://www.statistik.si/spearmanov-koeficient/ (accessed 12.10.2022).

Stepišnik, U., 2020. Kraška polja v Sloveniji. Dela, 53, pp. 23–43. DOI: 10.4312/dela.53.23-43.

Stepišnik, U., Ilc Klun, M., Repe, B., 2017. Vrednotenje izobraževalnega potenciala geodiverzitete na primeru Cerkniškega polja. Dela, 47, pp. 5–21.

SURS [Statistični urad Republike Slovenije = Statistical Office of the Republic of Slovenia], 2022. Prebivalstvo. URL: https://pxweb.stat.si/SiStat/sl/Podrocja/Index/100/prebivalstvo (accessed 15.09.2022).

Torabi Haghigi, A., Kløve, B., 2015. A sensitivity analysis of lake water level response to changes in climate and river regimes. Limnologica, 51, pp. 118–130.

Tratnik, D., 2023. Posegi na Cerkniškem jezeru (personal information, 22.11.2023). Cerknica.

Trobec, T., 2022. Vpliv podnebnih sprememb na vode v Sloveniji. Geomix, 29, 2, pp. 37–40.

Turk, J., Pipan, T., 2009. Cerkniško polje. URL: http://www.dedi.si/dediscina/9-cerknisko-polje (accessed 18.02.2022).

Van der Kamp, G., Keir, D., Evans, M. S., 2008. Long-term water level changes in closed-basin lakes of the Canadian prairies. Cannadian Water Resources Journal, 33, pp. 23–38.

Vertačnik, G., Bertalanič, R., 2017. Podnebna spremenljivost Slovenije v obdobju 1961-2011. Značilnosti podnebja v Sloveniji. Ljubljana: Agencija Republike Slovenije za okolje .

Vincent, W. F., 2009. Effects of climate change on lakes. In: Likens, G. E. (ed.). Encyclopedia of Inland Waters. Elsevier, pp. 55–60.

Wrzesiński, D., Ptak, M., 2016. Water level changes in Polish lake during 1976–2010. Journal of Geographical Sciences, 26, pp. 83–101. DOI: 10.1007/s11442-016-1256-5.

Zhelezov, G., Varbanov, M., Germ, M., Gaberscik, A. 2011. Hydrological characteristics and related ecosystem services of Srebarna and Cerknica lakes. Problems of geography, 1–2, pp. 107–118.