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Hydraulic Connectivity Between the Sava River and Lake Jarun During Drought: A High-Resolution Monitoring and Time Series Approach

Jelena Parlov[1]*, Filip Šegović[2], Kristijan Posavec[1], Zoran Kovač[1]

[1] *University of Zagreb, Faculty of Mining, Geology and Petroleum Engineering, Pierottijeva 6, HR10000 Zagreb, Croatia*
[2] *Croatian Geological Survey, Sachsova 2, 10000 Zagreb*

Abstract

This study offers the first detailed insight into the hydraulic relationship between the Sava River and Lake Jarun, an urban lake formed from a former river meander in Zagreb, Croatia. The main objective was to quantify and understand the temporal variability of their hydraulic connectivity under drought conditions. Continuous, high-resolution (hourly) water level monitoring of Lake Jarun, established in April 2022, was combined with interpolated Sava River water levels derived from national gauging stations. Using a suite of statistical tools – Pearson correlation, linear regression, cross-correlation, and the sliding window correlation method – the study assessed the strength, direction, and timing of river–lake interactions. The results revealed a clear but dynamic subsurface connection, with the lake typically responding to river fluctuations after a delay of five to six days. During the exceptional drought in the summer of 2022, this response weakened significantly, and the time lag extended beyond 21 days, indicating reduced hydraulic connectivity. The sliding window approach further revealed temporal variability, with sharp declines in correlation during low-flow periods and rapid recovery during high-water events. These findings highlight the non-stationary nature of hydraulic connectivity in regulated floodplains and the sensitivity of such systems to hydrological extremes. In addition to providing the first high-resolution dataset for Lake Jarun, this study introduces a time-adaptive analytical framework that enhances the understanding of short-term river–lake interactions and supports future management of urban water systems under increasing climatic pressure.

Keywords:
Hydraulic connectivity, River–lake interaction, Cross-correlation, Sliding window analysis, Drought impact

1. Introduction

Until 1899, the Sava River in the Zagreb region was an unregulated, meandering watercourse. Characterized by dynamic erosion and accumulation processes, the river frequently changed its course, eroding banks and forming new channels, oxbow lakes, sandbanks and islands. The course of the river in Zagreb was not a single, stable channel as we know it today, but rather a complex network of smaller streams and river arms whose position was constantly changing. The beginning of river regulation and the construction of embankments resulted in some of these channels and oxbow lakes being permanently cut off from the main riverbed. As a result, numerous artificial and semi-natural lakes were formed in the Zagreb area, which are directly related to the regulation of the Sava River and the gravel excavation for the embankment construction. However, no systematic monitoring of water levels or studies on the relationship between these lakes and the Sava River has been established.

Among these lakes, Jarun has a special significance for the City of Zagreb. Lake Jarun was originally created as part of the river regulation and has since developed into an important sport, recreational and cultural centre for the city's inhabitants. It is frequently used for water sports, leisure activities and events, making it an important social and environmental asset for the local community. The lake not only enhances the quality of life of Zagreb's residents but also plays an important role in the urban ecology by contributing to biodiversity and providing a green space that promotes both physical and mental well-being. Its continuing role in the city's urban water landscape highlights the need to understand its hydrological function, particularly in relation to the nearby Sava River.

In recent times, investigation of hydrological and hydrogeochemical characteristics of lakes, rivers and groundwater, their relationship, as well as their response to climate change, has been the focus of numerous research studies (**García-Alix et al., 2022; Kieu & Nguyen, 2024; Rex et al., 2024; Damanik et al., 2024; Mus-**

* Corresponding author: Jelena Parlov
e-mail address: jelena.parlov@rgn.unizg.hr

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tonen et al., 2024; Zhou et al., 2024; Hassan et al., 2024; Dialameh et al., 2025; Caroni et al., 2025). Lakes and wetlands that appear disconnected from rivers or surface water systems are often referred to as geographically isolated wetlands (**Tiner, 2003; Leibowitz, 2015**) and yet may be functionally connected via subsurface flow paths or episodic surface flooding (**Mushet et al., 2015; Rains et al., 2016**). Crucially, functional isolation cannot be inferred from geographic or morphological features alone, especially in complex floodplain systems where hydrogeological features allow for delayed or attenuated interactions (**Zhang et al., 2021**). Furthermore, the hydraulic connection between river and lake is not static, but exhibits pronounced temporal and spatial variability, influenced by both climatic events and anthropogenic changes (**Ward, 1989; Cohen et al., 2016; Leibowitz et al., 2018**). These dynamics form a continuum that determines how, when and to what extent one water body influences another.

Since the Sava once meandered through the area of the city of Zagreb and deposited sediments that today form the city's aquifer, and the river is still embedded in this aquifer today, it can be assumed that there is a hydraulic connection between the river and the nearby lakes. This is consistent with previous research done in the study area which showed that the Sava River is in a dynamic relationship with the Zagreb aquifer and it presents the main source of recharge (**Parlov et al., 2019; Buškulić et al., 2025**). It can also be assumed that recent lake sedimentation, characterised by the accumulation of fine-grained, organically enriched or silty material, clogs the bottom of the lake and weakens its connection with the surrounding waters. This semi-permeable layer significantly reduces hydraulic conductivity and prevents subsurface water exchange with neighbouring aquifers or the river system (**Packman et al., 2006**). As a result, it likely delays or dampens the hydraulic response of the lake to river water level fluctuations and weakens functional connectivity, especially at low water levels.

Despite many hydrogeological and hydrogeochemical studies conducted in the Zagreb area, no research has yet systematically examined the temporal variability of hydraulic connectivity between the Sava River and adjacent urban lakes. This represents a clear research gap, as understanding such temporal dynamics is essential for evaluating how urban floodplain systems respond to natural hydrological fluctuations and anthropogenic regulation.

Although different hydrogeological and hydrogeochemical studies have been done in the study area (**Parlov et al., 2019; Buškulić et al., 2023; Kovač et al., 2023; Buškulić et al., 2025**), the focus was not on the evaluation of the Sava River influence and its connectivity with lakes in the city of Zagreb. Accordingly, the main goal of this study is to quantify and characterise the dynamic hydraulic relationship between the Sava River and Lake Jarun using high-resolution water level data, with particular emphasis on drought and low-flow conditions. Specifically, the study aims to determine the temporal variability and responsiveness of the lake system to river fluctuations through advanced time-series analyses. This is extremely important because it can provide new insight into the variations of hydrological regime (**Chen et al., 2025**). By explicitly addressing this research gap, the study contributes to a better understanding of surface water interactions in a regulated, alluvial environment and provides a scientific foundation for the adaptive management of urban water resources under changing climatic conditions. Although this study builds on the authors' previous research on the hydrogeological and isotopic characteristics of the Zagreb aquifer system (**Parlov et al., 2019; Buškulić et al., 2023; Kovač et al., 2023; Buškulić et al., 2025**), it introduces a distinct focus and methodological advancement. Unlike earlier works, which primarily addressed groundwater recharge and geochemical processes, this paper explicitly quantifies and characterises the temporal dynamics of hydraulic connectivity between the Sava River and Lake Jarun using newly collected high-resolution (hourly) water level data and a time-adaptive sliding window correlation analysis. This approach and dataset are entirely novel and provide the first empirical evidence of river–lake interaction in this urban alluvial setting.

To empirically investigate this relationship and establish a foundation for long-term assessment, systematic monitoring of lake water levels was first initiated by **Šegović (2022)**. Building upon this, a continuous monitoring system was established at Lake Jarun with automatic water level gauge that have been recording hourly changes since April 7th, 2022. This represents the first long-term high-resolution (hourly) dataset available for Lake Jarun, providing a unique basis for assessing its hydraulic connectivity with the Sava River. In parallel, hourly water level data for the Sava River was obtained from the Croatian Meteorological and Hydrological Service (DHMZ). This double data set enabled a comprehensive statistical analysis of the hydraulic interaction between the two systems. The study uses a combination of established statistical techniques, namely correlation, linear regression and cross-correlation, to assess the direction, strength, and timing of the lake's response to river fluctuations. An important innovation in this context is the introduction of the sliding window correlation method. It was originally developed in fields such as climatology and neuroscience to analyse dynamic relationships between time series (**Bailly-Comte et al., 2011; Hutchison et al., 2013; Allen et al., 2014; Delbart et al., 2014; Vergara et al., 2019; Schrunner et al., 2025**). However, the sliding window correlation has rarely, if ever, been used to quantify the hydraulic interactions between rivers and lakes. By calculating Pearson correlation coefficients within successive, overlapping time windows, this method allows the detection of temporal variations in the strength of the lake–river connection. It

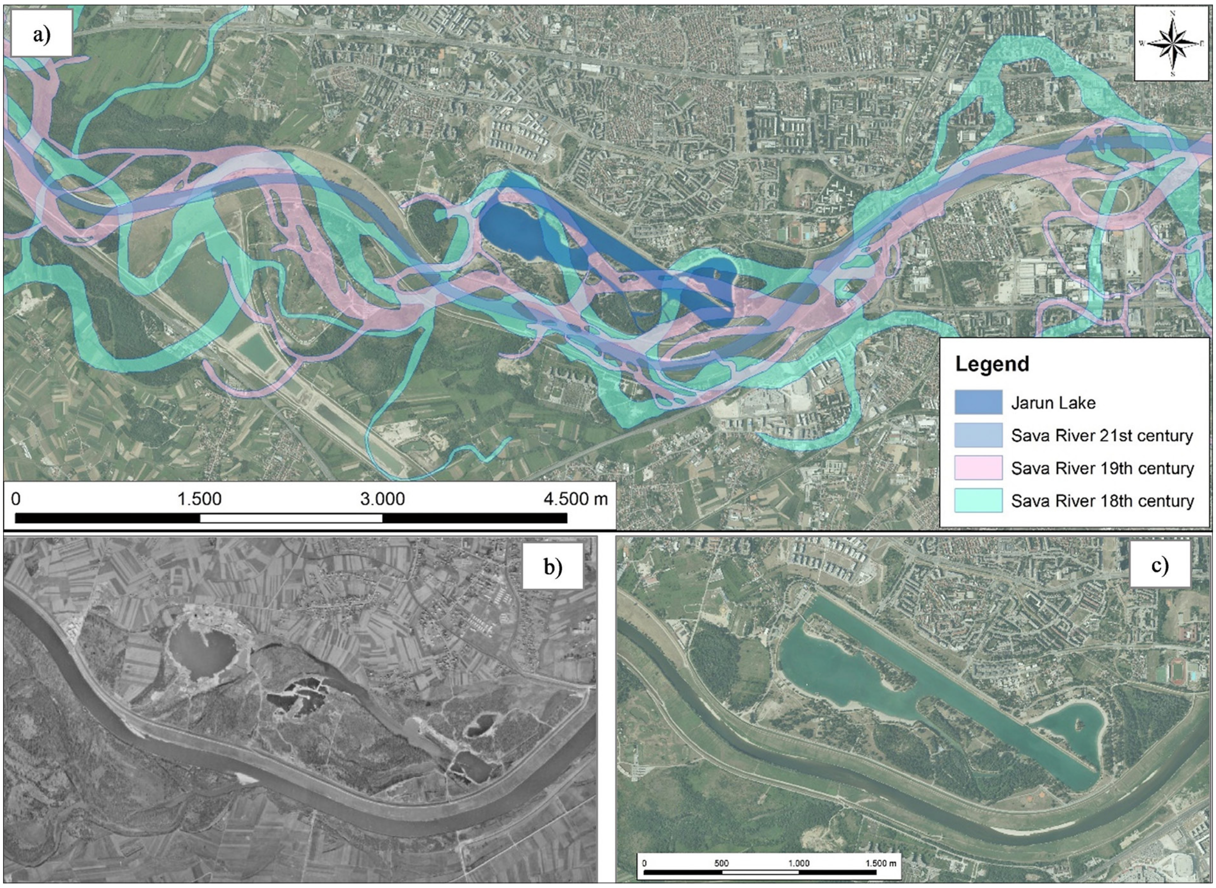

Figure 1. Lake Jarun (present state) in relation to the courses of the Sava River in the 18th, 19th and 21st centuries (a), Lake Jarun area on the aerial photograph from 1968 (b), Lake Jarun today (c)

is particularly useful in determining how droughts or high-water pulses affect the responsiveness of the lake system. The application of the sliding window correlation method provides new insight into the dynamic nature of river–lake hydraulic relationships in regulated, alluvial environments. In contrast to previous studies that primarily relied on temporally aggregated or static analyses of river–lake interactions, this research introduces a time-adaptive analytical framework based on the sliding window approach. This methodology enables the quantification of short-term variations and evolving correlations between hydrological systems, providing a more refined understanding of transient connectivity processes. By explicitly addressing the temporal dynamics of hydraulic coupling, the study advances current methodological practice and reinforces the importance of high-frequency monitoring data for capturing non-stationary hydrological behaviour. These findings offer a stronger empirical basis for adaptive management of urban water systems under increasing climatic and hydrological variability.

2. Materials and Methods

The methodological framework of this study was developed to investigate the hydraulic connection between the Sava River and Lake Jarun. As there has been no systematic monitoring of the lake to date, it was first necessary to reconstruct the broader historical and hydrogeological context of the area, followed by the establishment of a monitoring system that provides a comprehensive basis for quantifying the assumed river-lake interaction.

2.1. Historical Evolution and Regulation of the Sava River in the Zagreb Area

The current morphology and position of the Sava River in the Zagreb region differs considerably from its natural state before human intervention. In the past, the river meandered through a wide area bordered by the Medvednica Mountain, the Samobor Hills and the Vukomeričke Gorice, forming a dynamic river system. Over the last 10,000 years, these natural processes have led to the formation of three different alluvial terraces through the deposition of sediments transported from upstream. Today, these deposits form the so-called Zagreb alluvial aquifer. Through frequent lateral migration and channel shifts, the Sava River created numerous side channels, oxbow lakes, floodplains and gravel banks, thus forming a complex river landscape. Before regulation, the meandering course of the river through the city of Zagreb is well documented in historical topographical maps, on which the wide, shallow and branched channel is clearly recognisable (see **Figure 1a**).

It is important to note that the main channel of the Sava River once ran along the site of today's Lake Jarun (**Šimunjak, 2022**). As part of river regulation works in the early 20th century, this section was cut off from the active river regime by the construction of flood protection embankments and the straightening of the channel. This hydromorphological intervention transformed a formerly dynamic river corridor into an isolated remnant that later developed into a managed urban lake system (see **Figures 1b and 1c; URL 1**).

The first systematic regulatory measures were initiated in response to rapid industrialisation and a series of devastating floods, particularly in the spring and autumn of 1895. Official work began in 1899 and lasted until 1918. By 1900, significant infrastructure had already been completed, including embankments along the left bank of the river. This marked the beginning of the Sava's transition to its current linear form. By 1914, the river had transformed from a wide, shallow watercourse into a narrower and deeper channel. Most of the embankments had been completed before the outbreak of the First World War, but further development was interrupted by both world wars. The newly regulated canal significantly improved the water flow and reduced the frequency of flooding. However, in the absence of continuous embankments, extreme rainfall events still led to flooding in the areas south of the railway line in Zagreb (**Slukan Altić, 2010**).

The last major phase of river regulation, which included the construction of reinforced embankments, was carried out after the flood disaster of 1964, which inundated large parts of Zagreb. By 1967, the Jarun area had been secured with protective embankments that effectively protected it from future flooding. In 1984, the concept for the Jarun Sports and Recreation Centre (RSC Jarun) was officially presented as part of Zagreb's bid to host the 1987 Summer Universiade. This event marked the beginning of extensive construction work with the aim of transforming the former floodplain into a multifunctional complex for sports, recreation and water management. The development continued until the start of the Universiade in 1987, making Jarun an important part of Zagreb's modern urban landscape.

2.2. Hydrogeological Context of the Lake Jarun Area

During the Holocene, the hydrogeological and geomorphological development of the Zagreb Plain changed considerably. As climatic conditions became more favourable and tectonic activity altered drainage patterns, the Sava River established its present course through the region and began depositing extensive alluvial sediments in the floodplain (**Velić and Durn, 1993**). These Holocene deposits, which consist mainly of gravels and sands with intercalated silts and clays, today form the upper and most permeable aquifer system in this area. These deposits, which are characterised by high hydraulic conductivity - especially in the western parts of the aquifer where values exceed 3,000 m/day - were deposited by the Sava River during alternating periods of intense sediment transport and flooding (**Bačani and Posavec, 2014**). The river actively interacts with this aquifer system: when the water level is high, the Sava River recharges the aquifer along its entire course in the Zagreb area, while during prolonged low water levels it can act as a drainage axis and lower the groundwater level. This dynamic relationship between the river and the aquifer depends on factors such as the permeability of the sediments in the riverbed and the height of the groundwater table (**Posavec, 2006**).

Lake Jarun lies directly in this Holocene alluvium, which formed in a section of the former main channel of the river. Due to its location on highly permeable, gravel-dominated sediments and its origin as an abandoned meander, with no surface inflows and observed higher water levels during high Sava River levels and vice versa, a justified hypothesis is that Lake Jarun has a strong hydraulic connection with the Sava River. This hydraulic connection is most likely dominantly maintained via subsurface flow through the shared alluvial substrate, especially during periods of elevated river water levels. However, the strength of the hydraulic connection remains unconfirmed as there are currently no direct measurements or long-term data sets to confirm the presence, direction or extent of water exchange between the lake and the river. Given the geomorphological context of the lake and the known permeability of the surrounding sediments, Jarun is theoretically expected to behave as part of the broader Holocene alluvial system, in which interactions between river, lake and groundwater occurs. In this conceptual model, the water level of the lake responds - albeit with a time lag and attenuation - to fluctuations in the hydrological regime of the Sava River, presumably with a longer time lag under extreme hydrological conditions such as droughts or floods.

2.3. Establishment of Water Level Monitoring at Lake Jarun

Despite the importance of Lake Jarun for the hydrological and urban system of Zagreb, no systematic or long-term monitoring of its water level was carried out in recent decades prior to this study. In April 2022, a continuous water level monitoring programme was launched, which represents the first recorded hydrometric observation of Lake Jarun in recent history. An automatic water level logger was installed on April 7th, 2022, and has been operating continuously since then, collecting water level data every hour. The logger was installed in the centre of a bridge spanning the lake. It is housed in a protective PVC pipe that has been securely fastened to a concrete

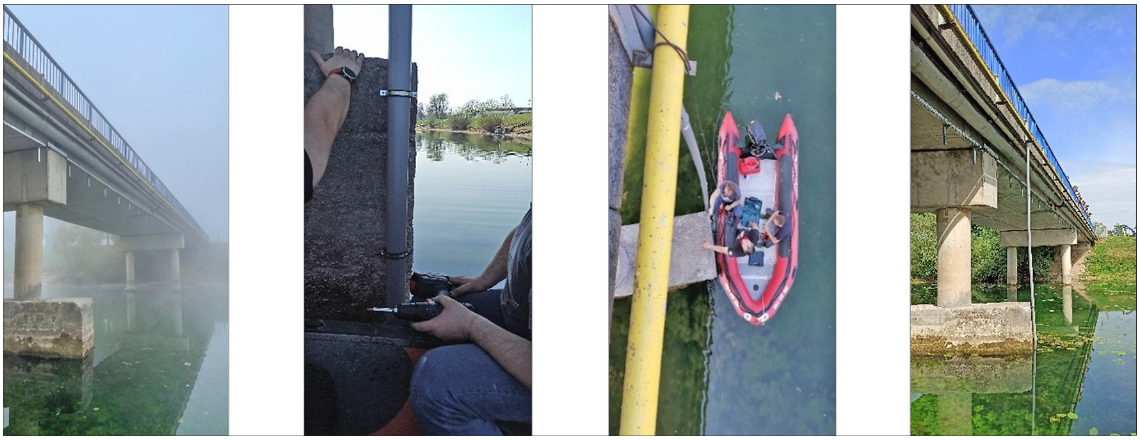

Figure 2. Installation of the automatic water level logger in Lake Jarun

platform and bridge pier to ensure physical stability and protection from external damage (see **Figure 2**).

This site was chosen for its accessibility, its protection from waves and its suitability for recording representative water levels in the main basin of the lake. The monitoring station provides high temporal resolution data, which is crucial for the assessment of seasonal and event-related fluctuations, especially during low water or drought, as well as for the study of the hydraulic relationship between the Lake Jarun and the nearby Sava River.

2.4. Approach for Verification and Quantification of the Hypothesized Hydraulic Connection

Although observations, the geomorphological features and sediment composition suggest a possible strong hydraulic connection between the Sava River and Lake Jarun, no analysis have yet been made to empirically quantify this interaction. The assumption of such a strong connection is primarily based on the location of the lake within a former main channel of the Sava River and the presence of highly permeable Holocene alluvial deposits shared by the river and the lake basin. Further, it can be observed that water level in the Lake Jarun rises when Sava River levels are high and vice versa.

A targeted observation campaign was launched to investigate this hypothesis and quantify Sava River - Lake Jarun hydraulic connection, using daily and hourly water level data. The water level data for the Sava was obtained from the Croatian Meteorological and Hydrological Service (DHMZ). The focus of the analysis was on low water level periods, which are defined as periods when the river level falls below the 10th percentile of observed values within the study period. To support this classification and ensure objective identification of low water level periods, a long-term water level duration curve (WLDC) was created based on historical water level data from the Sava, from 2000 to 2020.

2.5. Statistical Analysis of River–Lake Interaction

As Lake Jarun has not been monitored in recent decades, this study is the first attempt to confirm the existence of a hydraulic connection and to quantify the river–lake interactions in this area. The extreme hydrological conditions are particularly important to test for possible disruption of the river-lake connection or attenuation of the hydraulic response. The following methods were used to investigate the existence and characteristics of a possible hydraulic connection:

1. The correlation or statistical association describes the degree of interdependence between two measurable variables. In hydrological contexts, correlation analysis can be used to quantify the strength of the relationship between water systems (e.g. river and lake levels) and their boundary conditions. The strength of this connection can provide information on which system exerts a dominant influence or indicates the sensitivity of a lake or aquifer to external hydrological inputs and outputs. The correlation coefficient is a dimensionless statistical indicator that quantifies the strength and direction of a linear relationship between two variables, regardless of the units of measurement. In this analysis, the Pearson correlation coefficient was used, which was calculated using the CORREL function in Microsoft® Excel.

The coefficient ranges from +1 to −1, where +1 indicates a perfect positive linear relationship, −1 a perfect negative (inverse) relationship and values close to 0 indicating a weak or no linear association. Normally, correlation coefficients above 0.8 are considered strong, while values below 0.5 indicate weak relationships (**Davis, 2002**).

2. While correlation reveals the presence and direction of relationships, regression analysis is used to model and quantify these relationships, especially when the behaviour of a dependent variable is to be predicted on the basis of one or more independent variables. For example, the water level of a lake, dependent variable, can be predicted from the water level of a river, independent variable, using a simple linear regression:

$$y = \beta_0 + \beta_1 x + \varepsilon \quad (1)$$

where y is the dependent variable (e.g. lake level), x is the independent variable (e.g. river stage), β_0 and β_1 are

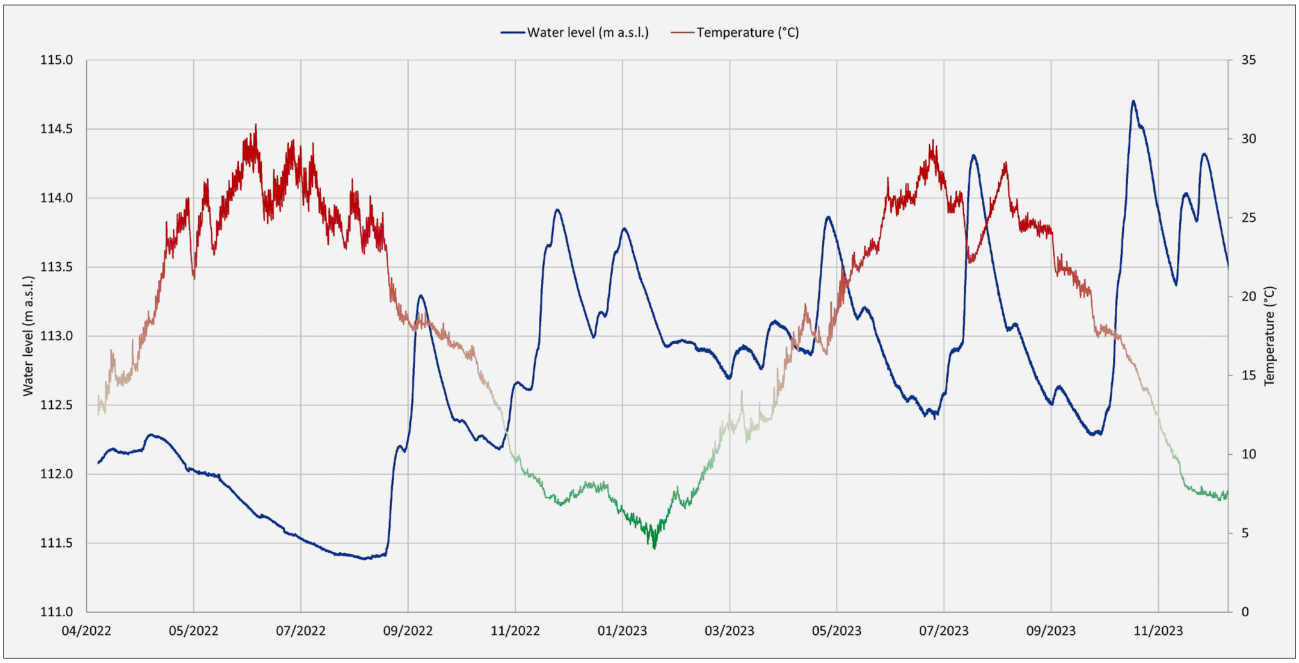

Figure 3. Hourly time series of water level and water temperature in Lake Jarun

regression coefficients, and ε is the random error term. This allows for assessing the influence of river input on lake level variation and is particularly valuable for forecasting and management (**Davis, 2002**).

3. Cross-correlation is used to analyse the time-delayed relationships between hydrological systems. This method is used to investigate how shifts in one time series (e.g. river levels) correspond to delayed responses in another (e.g. lake levels), revealing not only the strength but also the timing of their interaction. This is crucial when system responses are often delayed due to storage, flow paths or geological influences. In mathematical terms, cross-correlation quantifies the degree to which two data sets correlate depending on the time lag between them. The correlation coefficient r_{lag} is calculated for each time lag (positive or negative lag) so that the lag at which the maximum correlation occurs can be determined. This lag is interpreted as the transmission time of pressure changes through the aquifer system (**Davis, 2002**).

$$r_{lag} = \frac{cov_{xy}}{\sigma_x \sigma_y} \tag{2}$$

where r_{lag} is the correlation coefficient for each match position, cov_{xy} is the covariance between the two variables, and σ_x and σ_y are the standard deviations of the two-time series x and y, respectively.

The results are usually presented using a cross-correlogram, a graphical representation of the correlation coefficients over a series of time intervals. The first positive peak in the correlation diagram indicates the most likely lag in the response time between the variables, which is crucial for identifying cause-effect relationships in hydrogeological systems and supporting predictive modelling. A freely available VBA code in Excel published by **Posavec et al. (2017)** was used for the cross-correlation analysis.

4. To assess the temporal variability in the relationship between the water levels of river and lake, a sliding window Pearson correlation analysis was performed. The continuous time series was divided into overlapping windows of different lengths: 5, 10, 15, 20, 25, 30 and 35 days. Within each window, the Pearson correlation coefficients between the water levels of river and lake were calculated. This approach allowed the detection of changes in the strength of the correlation over time and provided insight into whether the lake's response to river fluctuations was consistent or varied under different hydrological conditions. Particular attention was given to periods of lower correlation that coincided with lower river levels, indicating possible changes in hydraulic connectivity or responsiveness of the lake system during low water level periods.

These complementary approaches aim to provide both statistical evidence and hydrological interpretations of the hypothesised river-lake interaction. Together, they represent not only a first but also a structured step towards understanding river-lake dynamics in the Holocene alluvial system of western Zagreb.

3. Results and discussion

The installed measuring system has been providing a continuous data set with hourly water level and water temperature measurements for Lake Jarun since April 7th, 2022. This long-term monitoring covers both low water and high water periods and provides valuable in-

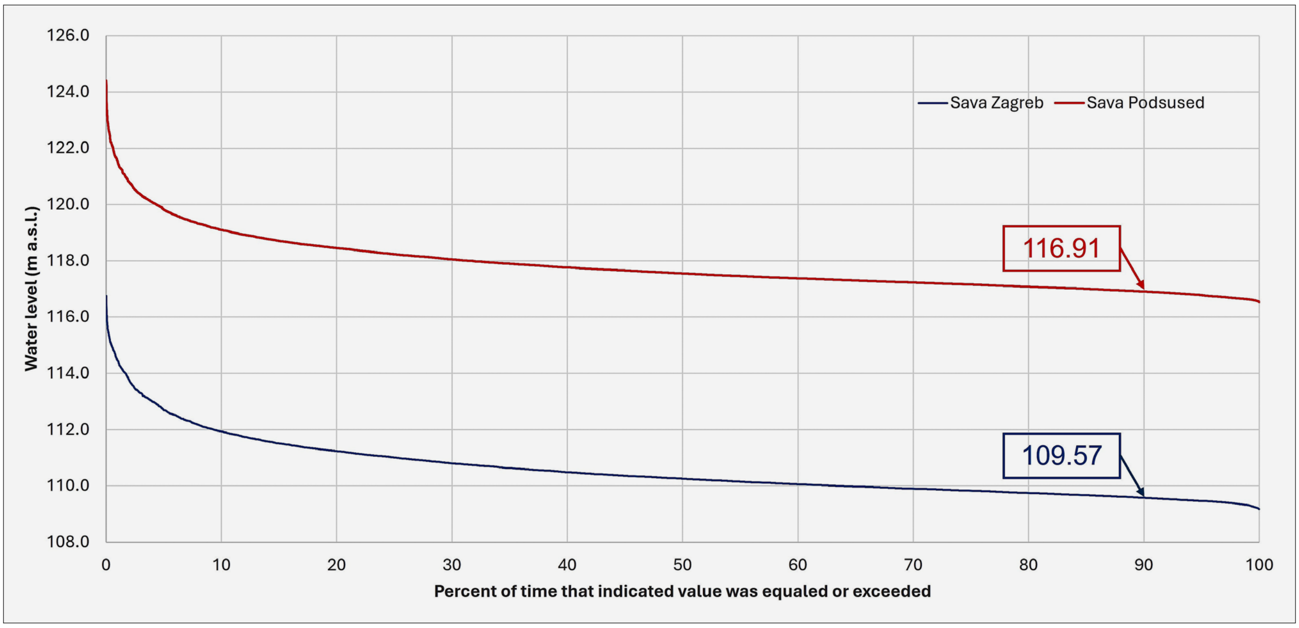

Figure 4. The water level duration curves (WLDC) created using the long-term historical water level data from 2000 to 2020

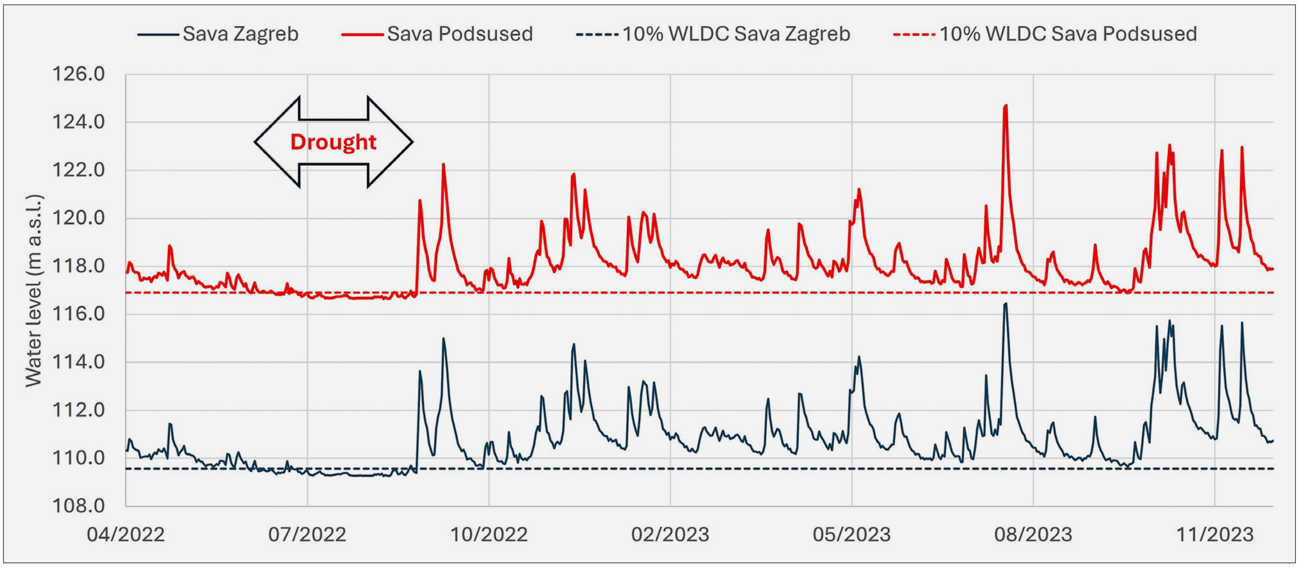

Figure 5. Water levels of the Sava at the Zagreb and Podsused stations with threshold values that indicate extreme drought in 2022

sight into the lake's response to a range of hydrological conditions. The recorded water levels show the expected seasonal and short-term fluctuations, with the fluctuations being more pronounced during high water events. In parallel, the water temperature data clearly reflect the seasonal transitions and show a consistent change between warmer and colder periods of the year. These patterns are illustrated in **Figure 3**, which shows the temporal dynamics of both variables from April 7th, 2022, to December 2023.

This extended dataset provides a solid basis for further correlation analyses aimed at characterising the hydraulic interaction between Lake Jarun and the Sava River across different hydrological regimes. Given the assumption that a strong hydraulic connection exists, supported by past observations, geological, historical and geomorphological evidence, the data provide the opportunity to empirically test and quantify this interaction, particularly during stress conditions such as drought. In order to conduct a meaningful correlation analysis focussing specifically on low water level conditions, it was first necessary to objectively define what constitutes a drought or low water level period for the Sava River in the study area. For this purpose, water level duration curves (WLDC) were created based on long-term historical water level data from 2000 to 2020,

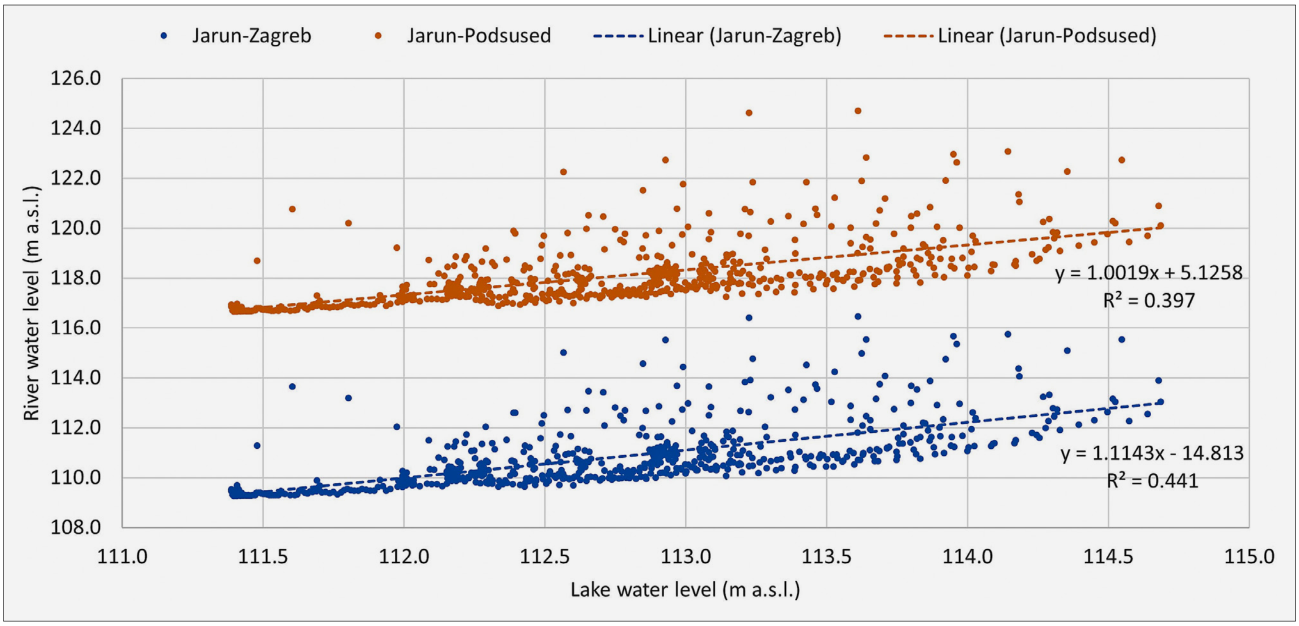

Figure 6. Linear regression between the water levels of the river Sava and Lake Jarun

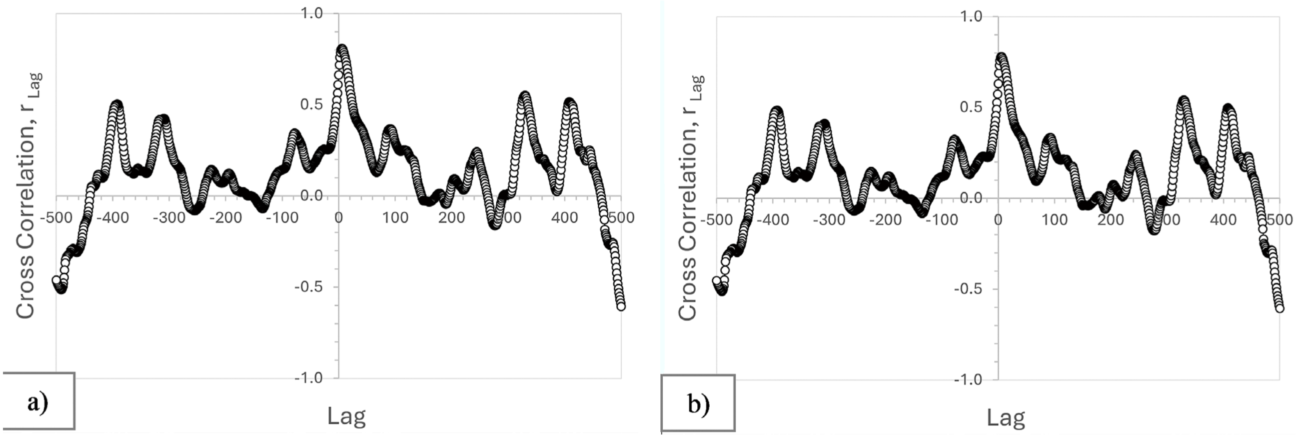

Figure 7. Cross-correlogram of Zagreb-Jarun (a) and Podsused-Jarun (b) – daily values

obtained from two nearby gauging stations (Zagreb and Podsused) and provided by the Croatian Meteorological and Hydrological Service (DHMZ). These curves are shown in **Figure 4**.

As already described in the theoretical framework, low water level periods are defined as intervals in which the river level falls below the 10th percentile of the observed values. Based on the WLDC analysis, this threshold corresponds to a water level of 116.91 m a.s.l. at the Podsused station and 109.57 m a.s.l. at the Zagreb station. The determined 10-percentile threshold values served as objective reference values for recognising extremely low water levels. These threshold values made it possible to determine specific time intervals in which extreme dryness prevailed. This is illustrated in **Figure 5**, which shows the daily water level time series of the Sava at both stations together with the respective threshold lines. It can be seen from the graph that a prolonged period of extremely low water levels occurred between June and September 2022, representing one of the most hydrologically stressed intervals within the monitoring period. It must be emphasized that drought happened in 2022 has been identified as one of the most severe in other parts of the world (**Chen et al., 2025**). This identified drought window was then used as a focus for a detailed correlation analysis between the Sava River and Lake Jarun.

In a first step, the relationship between the Sava River and Lake Jarun was assessed using the complete set of the daily water level data from the official gauging stations Zagreb and Podsused and the corresponding daily mean values from the automatic logger of Lake Jarun for the period from 04/2022 until 11/2023. Pearson correlation coefficients were calculated to assess the linear relationships. The values obtained were 0.66 for Zagreb and 0.63 for Podsused, indicating a moderate correlation between river and lake water levels on the daily scale. Linear regression analyses were also performed. The results

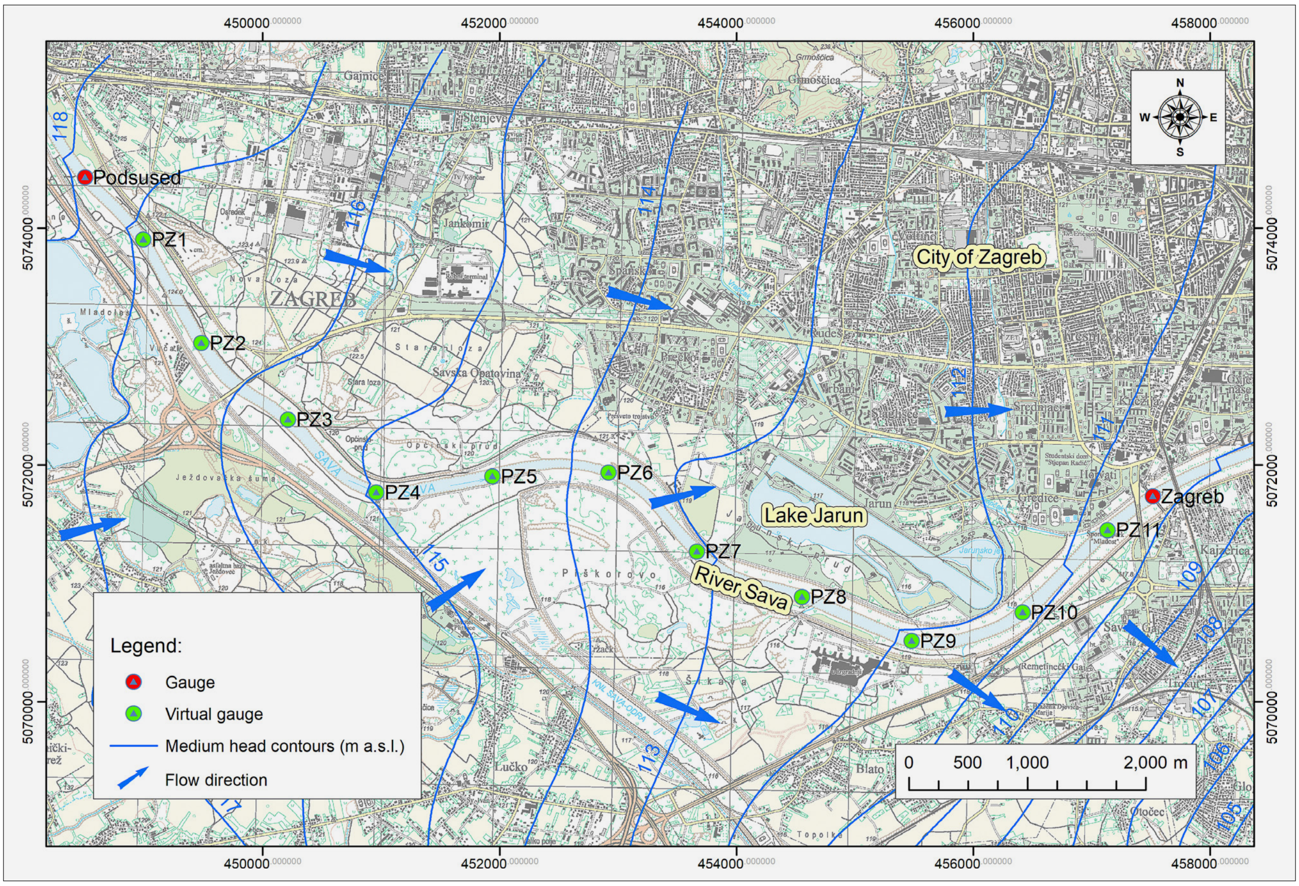

Figure 8. Virtual gauging stations and medium head contours near Lake Jarun

are presented in **Figure 6**, which shows scatter plots with regression lines and coefficients of determination (R^2) for both combinations of station and lake. In addition, a cross-correlation analysis was performed to investigate possible delayed responses between river and lake levels over daily time scales. The results showed that the maximum correlation between Jarun and the Zagreb station occurred with a lag of six days, as well as with the Podsused station, with corresponding coefficients of 0.806 and 0.781, respectively. The cross-correlation curves are shown in **Figure 7**. The correlation and regression analyses based on the daily data from the Zagreb and Podsused gauging stations showed moderate positive correlations with the lake level as well as relatively strong cross-correlation peaks with a lag of six days. These results indicate a delayed but stable interaction under typical hydrological conditions. They reflect subsurface flow processes through the common alluvial aquifer and the time required for pressure signals to propagate through the unconfined Holocene alluvial aquifer that underlies both the river and the lake. The presence of such a time lag is consistent with earlier results by **Posavec et al. (2017)**, who performed a cross-correlation analysis between the Sava River and nearby groundwater levels in the area between the river and Lake Jarun. Their work also showed delayed responses, supporting the hypothesis of indirect but functional hydraulic connectivity determined by the dynamics of the unconfined alluvial aquifer.

Although the Zagreb and Podsused gauging stations provide reliable long-term data, both are located at a considerable distance from Lake Jarun, which limits their representativeness for local hydraulic assessments. To improve the spatial resolution and better represent the river conditions in the vicinity of the lake, in the second step, a series of virtual gauging stations were set up along the Sava River between upstream Podsused and downstream Zagreb gauging stations. These virtual stations were positioned at 1,000 metre intervals between the Zagreb and Podsused stations (see **Figure 8**). For each position, the corresponding water level was estimated by linear interpolation of the measured values at the two reference stations. Linear interpolation method provided a reasonable estimate of water levels since no natural or artificial barriers like waterfalls, weirs or dams in the Sava watercourse between Zagreb and Podsused stations exist. This method provided a continuous spatial profile of water levels along the interpolated river section. Taking into account predominant general groundwater flow direction between the Sava River and Lake Jarun, i.e. from west to east, as well as the relative location of Lake Jarun within the interpolated section, the station labelled PZ6 (see **Figure 8**) was selected as the reference point for further correlation analysis, where

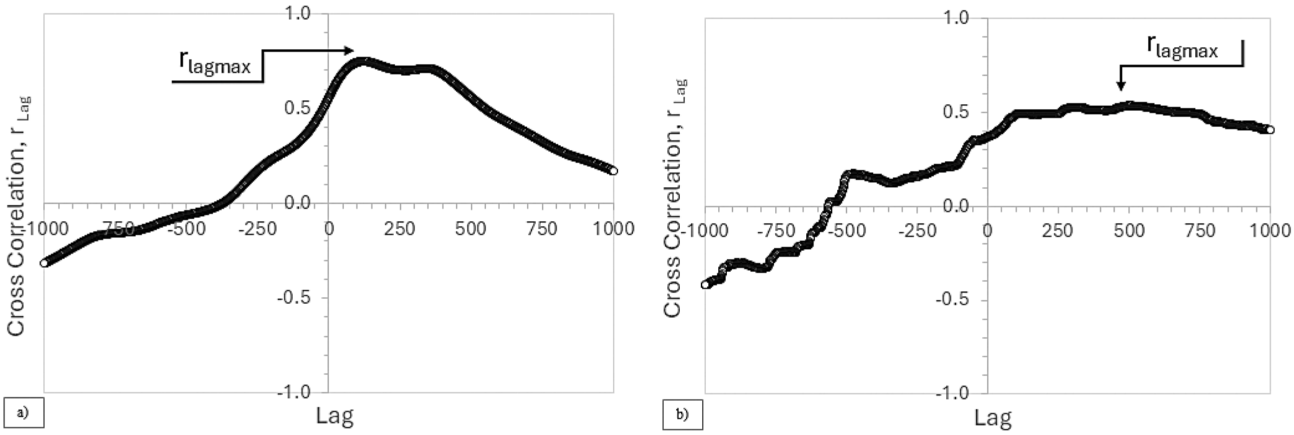

Figure 9. Cross-correlogram of PZ-6-Jarun – hourly values: all data (a), drought period (b)

the figure also shows the medium head contours illustrating the general groundwater flow pattern. This allowed for a more detailed investigation of the potential hydraulic interactions between the Sava River and Lake Jarun during the extreme drought period in 2022.

Further, in order to investigate possible short-term hydraulic reactions between the Sava River and Lake Jarun, a cross-correlation analysis was carried out using hourly water level data from the virtual station PZ6 and the lake. The analysis was performed in two phases. First, the entire available monitoring period was analysed to capture the general pattern of lagged interactions. The resulting cross-correlation function showed a maximum correlation at a delay of 120 hours (5 days) with a correlation coefficient of 0.748 (see **Figure 9a**), which corresponds exactly to the delay of six days observed in the daily data. This consistency between the different temporal resolutions emphasises the robustness of the identified relationship. Subsequently, in the second phase the same method was applied to a more hydrologically critical period - the extreme drought window from June 15th to September 15th, 2022. During this period, the cross-correlation showed a maximum at a lag of 504 hours (21 days) with a coefficient of 0.54 (see **Figure 9b**), indicating that the lake becomes more disconnected from the river system under hydrological stress conditions. This longer delay can be attributed to several factors, including a lower hydraulic gradient between the river and the lake during low water levels as well as the fact that during low water levels of the lake, groundwater–lake interaction predominantly occurs through the bottom of the lake which is mudded while during higher water levels in the lake, groundwater–lake interaction occurs also through the lake shores which are made of sand and gravel, making interactions stronger due to higher hydraulic conductivities of sands and gravels. As mentioned in the introduction, recent sedimentation, particularly of fine-grained, organically enriched material, can form a semi-permeable layer on the lake bottom (**Packman et al., 2006**). This layer reduces permeability, impedes subsurface flow and reduces the responsiveness of the lake to external fluctuations. In fact, during a drought, the system behaves more like a geographically isolated lake, which is geographically close to a large river but functionally more disconnected. As **Leibowitz (2018)** and **Zhang et al. (2021)** emphasise, the appearance of isolation can be misleading, since hydraulic connectivity is often governed by subtle subsurface processes that can weaken or strengthen over time. The Jarun-Sava system vividly illustrates this complexity. This behaviour clearly shows how sensitive the hydraulic connectivity is to external stressors, especially prolonged periods of low flow levels and limited recharge.

To investigate the temporal variability of the hydraulic relationship between the Sava River and Lake Jarun, a Pearson correlation analysis with sliding windows was performed for the entire data set of hourly water levels. The correlation coefficients were calculated in overlapping time windows of 5, 10, 15, 20, 25, 30 and 35 days. The results for all window lengths are shown in **Figure 10**, which shows the development of the correlation values over time on different temporal scales. The analysis revealed clear periods of decreasing correlation, especially in the summer months of 2022, which coincided with the previously identified extreme drought period. During these periods, the correlation coefficients decreased significantly across all window sizes, indicating a weakening hydraulic connection or a delayed response of the lake system at low river levels. This observation is consistent with the results of the cross-correlation analysis, which indicates longer lag times under drought conditions. Conversely, a strong increase in correlation strength was observed when river levels rise, indicating a rapid hydraulic response of the lake to rising river levels. This pattern was particularly evident in shorter time windows (5-10 days), highlighting the sensitivity of lake-river interaction to sudden hydrological influences. The sliding window approach therefore provides a dynamic view of the system's behaviour and shows that the strength and consistency of the hydraulic connection varies considerably over time, mainly due to the river's flow regime.

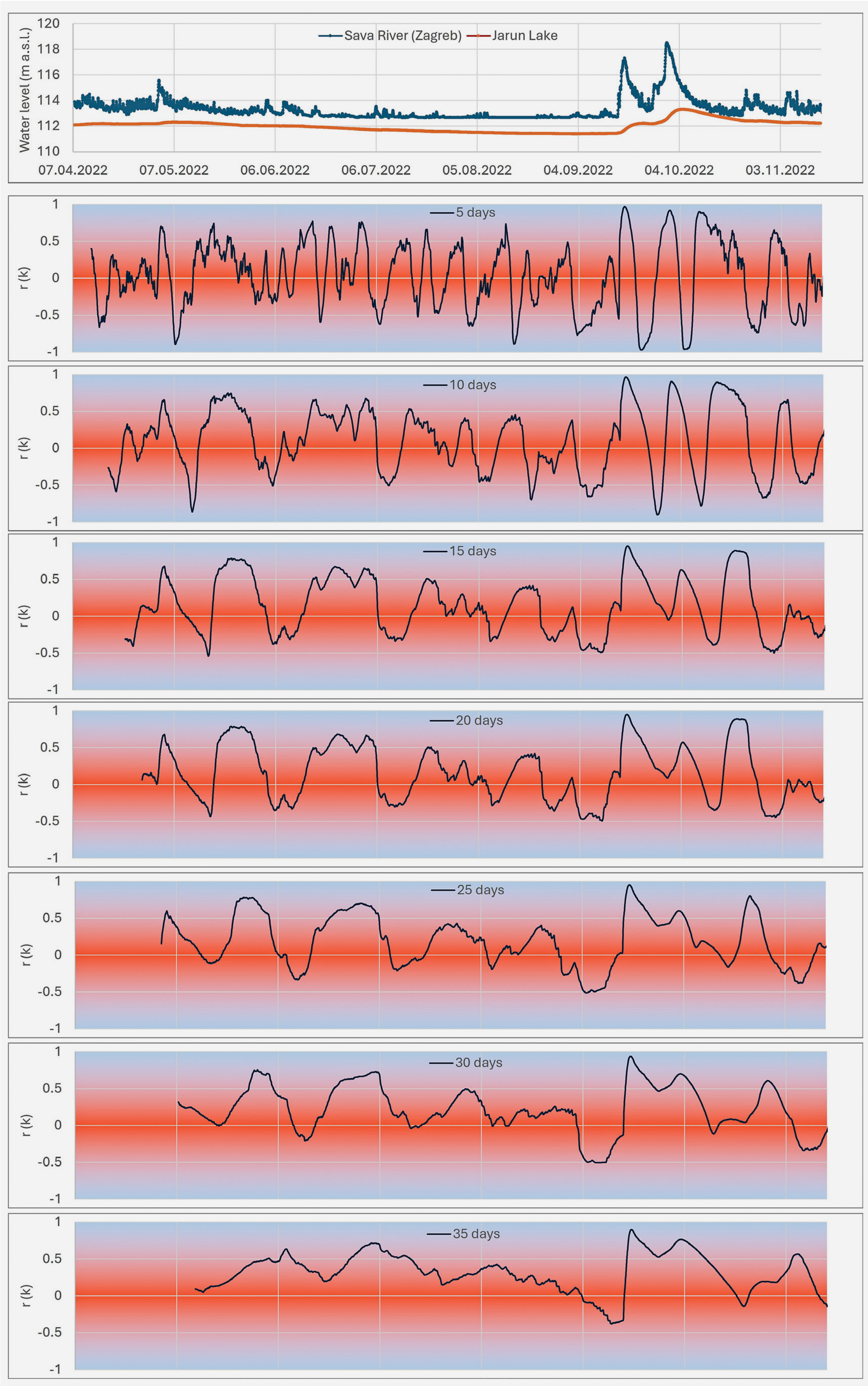

Figure 10. Sliding window correlation between the water levels of the Sava River and Lake Jarun for different window lengths (5, 10, 15, 20, 25, 30 and 35 days)

These findings reinforce a growing recognition in hydrological science that connectivity is not static but varies at both spatial and temporal scales (**Ward, 1989; Cohen et al., 2016**). With this in mind, Lake Jarun exhibits the same characteristics as so-called geographically isolated wetlands, i.e. systems that have no surface outflows or inflows but have episodic or permanent subsurface connectivity depending on climatic conditions. As **Mushet et al. (2015)** and **Rains et al. (2016)** have noted, such systems play an important hydrological and ecological role, even if their connections are only subtle or temporary. Lake Jarun seems to fit into this conceptual framework, particularly in times of hydrological stress.

The results of this study provide convincing evidence of a measurable, albeit temporally variable, hydraulic relationship between the Sava River and Lake Jarun. By combining long-term monitoring data with statistical methods, the study has successfully characterised how this relationship manifests itself under different hydrological regimes, with a particular focus on low flow conditions (drought). However, under extreme drought, the lake's response becomes delayed, weakened and less predictable - typical characteristics of isolated or weakly connected systems.

The differences in response times and correlation strength between the different hydrological regimes emphasise the importance of both spatial and temporal resolution in hydrological studies. While coarse resolution data is sufficient for general connectivity assessments, higher resolution time series in combination with spatially refined representations such as virtual stations are crucial to detect subtle or time-sensitive interactions. The results of this study highlight the vulnerability of shallow lake–aquifer systems in urban floodplains, especially given the projected increase in the frequency of droughts due to climate change.

To summarise, this study not only characterizes the strength of a hydraulic connection between the Sava River and Lake Jarun under normal flow conditions, but also shows that this connection becomes weaker and more delayed during extreme low flow events. These results have practical implications for future monitoring strategies and the management of water resources in urban alluvial areas. The observed variability in lag time and correlation strength highlights the sensitivity and vulnerability of river–lake interactions to hydrological extremes, with potential implications for groundwater recharge dynamics and aquifer sustainability in future climate-induced stress periods.

In addition, the planned dredging and cleaning of the lake bottom, which aims to remove accumulated sediments and increase the depth of the lake, raises important questions about the future hydraulic behaviour of the system. Such interventions are likely to alter the physical structure and permeability characteristics of the lake bottom sediment, potentially enhancing or disrupting current subsurface flow pathways that facilitate interaction with the Sava River. A deeper and potentially more permeable lakebed could increase the sensitivity of the system to prolonged droughts, as larger amounts of stored water could become more vulnerable to seasonal fluctuations. It remains to be seen whether this intervention strengthens or weakens the hydraulic connection, but it clearly emphasises the need for continuous high-resolution monitoring and reassessment of lake–river dynamics following anthropogenic changes.

4. Conclusions

This study presents the first detailed, data-driven assessment of hydraulic connectivity between the Sava River and Lake Jarun, combining continuous, high-resolution water level measurements with correlation-based time series analyses. The monitoring system, established in April 2022, has provided the first uninterrupted hourly dataset for Lake Jarun, covering both low- and high-water periods. By applying correlation, regression, and cross-correlation analyses to daily and hourly data, the study confirms a measurable but variable subsurface connection between the river and the lake.

Under typical hydrological conditions, a consistent response lag of approximately five to six days was identified between the river and the lake, reflecting the propagation of pressure signals through the shared unconfined alluvial aquifer. During the extreme drought in the summer of 2022, this connection weakened and the response lag increased to around 21 days, indicating reduced hydraulic gradients and a temporary decline in connectivity. The longer delay can be attributed to changes in groundwater–lake exchange pathways: during low lake levels, the exchange occurs mainly through the fine-grained, low-permeability lake bottom, whereas under higher levels, the water exchange extends to the sandy and gravelly shores with higher hydraulic conductivities, resulting in a stronger and faster response.

The introduction of the sliding window correlation method provided new insight into the temporal variability of hydraulic connectivity. This approach revealed clear fluctuations in correlation strength, with pronounced decreases during low-flow periods and rapid recovery during high-flow events. These results demonstrate that hydraulic connectivity between the river and lake is not constant but evolves dynamically under changing hydrological conditions. The use of virtual gauging stations between the Zagreb and Podsused sites further improved the spatial resolution of the analysis and confirmed that local river levels near Jarun exert the dominant control on lake fluctuations.

These findings provide the empirical basis for a new, time-adaptive framework to quantify dynamic river–lake interactions in urban floodplain settings. However, the study is limited by its relatively short monitoring period and its focus on a single site. Future research should therefore extend the temporal coverage, incorporate isotopic and hydrogeochemical tracers, and include simultaneous groundwater observations to fully capture the river–aquifer–lake continuum.

With planned interventions to dredge and deepen the lake bottom, continuous hydrometric monitoring will be essential to reassess connectivity and manage potential changes in lake–river exchange. Overall, this research establishes Lake Jarun as a model system for understanding time-variable hydraulic interactions in regulated floodplains and demonstrates that the Sava–Jarun connection, though persistent, is sensitive to drought and climatic extremes. Sustained high-resolution observation and the use of adaptive analytical approaches remain key to ensuring informed, resilient management of urban water systems.

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SAŽETAK

Hidraulička povezanost rijeke Save i jezera Jarun tijekom suše: pristup visokorezolucijskoga monitoringa i analize vremenskih nizova

Ovo istraživanje donosi prvi detaljan uvid u hidraulički odnos između rijeke Save i jezera Jarun, urbanoga jezera nastaloga iz nekadašnjega riječnog meandra u Zagrebu. Glavni cilj bio je kvantificirati i razumjeti vremensku promjenjivost njihove hidrauličke povezanosti, osobito u uvjetima suše. Kontinuirano, visokorezolucijsko (satno) praćenje razine vode u jezeru Jarun, započeto u travnju 2022. godine, kombinirano je s interpoliranim razinama vode rijeke Save dobivenima iz nacionalnoga monitoringa. Primjenom niza statističkih metoda – Pearsonove korelacije, linearne regresije, kroskorelacije i metode korelacije pomičnoga prozora – procijenjena je jačina, smjer i vremenski odaziv interakcije između rijeke i jezera. Rezultati su pokazali jasnu, ali dinamičnu podzemnu povezanost, pri čemu je razina jezera uobičajeno reagirala na promjene vodostaja rijeke s odgodom od pet do šest dana. Tijekom iznimne suše u ljeto 2022. godine ta je povezanost znatno oslabjela, a vremenska se odgoda produljila na više od 21 dan, što upućuje na smanjenje hidrauličke povezanosti. Metoda korelacije pomičnoga prozora dodatno je otkrila vremenske varijacije, s izraženim padom korelacije tijekom razdoblja niskih voda i brzim oporavkom tijekom visokih voda. Ovi rezultati naglašavaju nestacionarnu prirodu hidrauličke povezanosti u reguliranim poplavnim ravnicama te osjetljivost takvih sustava na hidrološke ekstreme. Uz to što pruža prvi visokorezolucijski skup podataka za jezero Jarun, ovo istraživanje uvodi vremenski prilagodljiv analitički okvir koji produbljuje razumijevanje kratkoročnih interakcija rijeke i jezera te podupire buduće upravljanje urbanim vodnim sustavima pod sve većim klimatskim pritiscima.

Ključne riječi:
hidraulička povezanost, odnos rijeka – jezero, kroskorelacija, analiza pomičnoga prozora, utjecaj suše

Author's contribution

Jelena Parlov (Professor): conceptualization, formal analysis, writing – original draft and writing. **Filip Šegović** (Expert associate): investigation, visualization and writing – review & editing. **Kristijan Posavec** (Professor): writing – review & editing. **Zoran Kovač** (Associate professor): investigation, resources and writing – review & editing.
All authors have read and agreed to the published version of the manuscript.