UDK/*UDC*: 551.58:556.5(282)(497.4)(497.5)
Izvirni znanstveni članek – *Original scientific paper*
DOI: 10.15292/acta.hydro.2025.02

Prejeto/*Received:* 29.03.2025
Sprejeto/*Accepted:* 06.05.2025
Objavljeno na spletu/*Published online:* 26.05.2025

COMPARATIVE HYDROLOGICAL ANALYSIS AT TWO STATIONS ON THE BOUNDARY RIVER SOTLA/SUTLA (SLOVENIA–CROATIA)

PRIMERJALNA HIDROLOŠKA ANALIZA NA DVEH POSTAJAH OB MEJNI REKI SOTLA/SUTLA (SLOVENIJA–HRVAŠKA)

Ognjen Bonacci[1], Ana Žaknić-Ćatović[2, *], Tanja Roje-Bonacci[1]

[1] Faculty of Civil Engineering, Architecture and Geodesy, Split University, 21000 Split, Matice hrvatske 15

[2] Department of Physical and Environmental Sciences, University of Toronto Scarborough, 1265 Military Trail, Toronto, ON M1C 1A4

Abstract

This study examines hydrological processes at the Zelenjak (1958–2023) and Rakovec (1926–2022) stations on the Sotla/Sutla River, analyzed on an annual time scale. The analysis includes time series of annual minimum and maximum mean daily flows and mean annual flows. Additionally, data on annual precipitation and mean annual temperatures measured at the climatological station Bizeljsko in the period 1951 to 2024 were used to calculate annual runoff coefficients at the Zelenjak and Rakovec stations. The New Drought Index (NDI) was calculated using precipitation and air temperature data measured at the Bizeljsko climatological station. All analyses indicated a strong variability of the analyzed parameters over the available data period. A clear downward trend in mean annual flows is observed. In the recent period, from 2000 onward, there has been a sharp increase in mean annual air temperatures and a decline in all other analyzed hydrological and climatological parameters. Particularly concerning is the notable rise in the frequency and intensity of droughts in the 2000–2024 period. The causes of these trends could not be reliably determined through an analysis conducted on an annual time scale. It appears that natural factors, particularly the sharp rise in air temperatures, have played a significant role. However, it is important to emphasize that the natural characteristics of the Sotla/Sutla River basin have, to date, remained largely unaffected by human interventions. Furthermore, the insufficient accuracy in defining peak flows must be considered, as the rating curves used to define maximum flows may not have been reliable in certain periods.

Keywords: flow, air temperature, precipitation, Sotla/Sutla River, Zelenjak and Rakovec gauging stations, climatological station Bizeljsko.

Izvleček

Študija preučuje hidrološke procese na postajah Zelenjak (1958–2023) in Rakovec (1926–2022) na reki Sotli/Sutli, analizirane na letni ravni. Analiza zajema časovne vrste najmanjših in največjih letnih srednjih

[*] Stik / *Correspondence*: ana.zaknic.catovic@utoronto.ca

dnevnih pretokov ter srednjih letnih pretokov. Podatki o letnih padavinah in srednjih letnih temperaturah zraka, zabeleženih na klimatološki postaji Bizeljsko v obdobju 1951–2024, so bili uporabljeni tudi za izračun letnih količnikov odtoka na postajah Zelenjak in Rakovec. Novi indeks suše (NDI) je bil izračunan na podlagi podatkov o padavinah in temperaturi zraka, izmerjenih na klimatološki postaji Bizeljsko. Vse analize so pokazale izrazito spremenljivost analiziranih parametrov v obdobju razpoložljivih podatkov. Opazen je izrazit trend upadanja srednjih letnih pretokov. V zadnjem obdobju, od leta 2000 naprej, je prišlo do izrazitega dviga srednjih letnih temperatur zraka ter upada vseh drugih analiziranih hidroloških in klimatoloških spremenljivk. Še posebej zaskrbljujoče je znatno povečanje pogostosti in intenzivnosti suš v obdobju 2000–2024. Vzrokov za te trende ni bilo mogoče zanesljivo določiti z analizo na letnem časovnem nivoju. Kaže, da so imeli pomembno vlogo naravni dejavniki, predvsem močan dvig temperature zraka. Vendar je treba poudariti, da naravne značilnosti porečja reke Sotla/Sutla do danes v veliki meri niso bile spremenjene zaradi antropogenih vplivov. Poleg tega je treba upoštevati nezadostno natančnost pri določanju koničnih pretokov, saj pretočne krivulje, uporabljene za določanje maksimalnih pretokov, v določenih obdobjih morda niso bile zanesljive.

Ključne besede: pretok, temperatura zraka, padavine, reka Sotla/Sutla, merilni postaji Zelenjak in Rakovec, klimatološka postaja Bizeljsko.

1. Introduction

The Sotla/Sutla River (Slovenian: Sotla; Croatian: Sutla) is a left tributary of the Sava River, serving as a border watercourse between Slovenia and Croatia. This transboundary nature underscores the need for reliable knowledge and continuous monitoring of its natural characteristics, particularly its hydrological properties. The Sotla/Sutla River and its tributaries are entirely part of the Natura 2000 protected area (HR2001070 and SI3000303), designated for the conservation of important animal and plant species as well as their habitats. Within the Sotla/Sutla River basin, several additional Natura 2000 sites exist: (1) Cret Dubravica (HR2000670); (2) Dobrava–Jovsi (SI3000268 and SI5000032); (3) Razvor (HR2001348); (4) Kozjansko (SI5000033); (5) Orlica (SI3000273). For approximately 80 km, the river serves as the border between Slovenia and Croatia.

The Sotla/Sutla River basin is bordered by the Dravinja River basin to the north, the Savinja River basin to the west, and the Krapina River basin to the east. The basin is asymmetrical, with dominant right-bank (western) tributaries, while left-bank tributaries are shorter and have small catchment areas. The total basin area is 581 km², with 451 km² located in Slovenia (Project FRISCO, 2017). Other sources report different figures; for example, the Croatian Encyclopedia reports that the basin covers 582 km², with 343 km² located in Croatia. According to Čosić-Flajsig et al. (2021), the Sotla/Sutla basin spans 590.6 km², with 78% (460.7 km²) in Slovenia and 129.9 km² in Croatia. Prah et al. (2013) estimate the basin at 583.8 km², with 81.7% (477 km²) within Slovenia (Figure 1).

The reported length of the Sotla/Sutla River varies across different sources ranging from 90 km (Project FRISCO, 2017), 91 km (Dragun et al. 2011; Čosić-Flajsig et al. 2017), and 92.4 km (Croatian Encyclopedia) to 95.486 km (Žiger and Bognar, 2007).

The elevation of the source, located in Slovenia, varies across the literature, ranging from 625 m a.s.l. (Žiger & Bognar, 2007) and 640 m a.s.l. (Projekt FRISCO, 2017) to 715 m a.s.l. (Croatian Encyclopedia) and 717 m a.s.l. (Čosić-Flajsig et al., 2017). Similarly, the reported elevation of the Sotla/Sutla River's confluence with the Sava River also varies, ranging from 112 m a.s.l. (Čosić-Flajsig et al., 2017) to 130 m a.s.l. (Project FRISCO, 2017) and 132.5 m a.s.l. (Žiger and Bognar, 2007).

Figure 1: ***(a)*** *The hydrographic map of Croatia with the Sotla/Sutla River watershed marked; (b) Map of the Sotla/Sutla watershed showing the locations of the Zelenjak (Croatia) and Rakovec (Slovenia) hydrological stations, as well as the Bizeljsko (Slovenia) climatological station; (c) Photograph of the Zelenjak hydrological station (Croatia); (d) Photograph of the Rakovec hydrological station (Slovenia; (e) Aerial view of the Sotla/Sutla River.*

Slika 1: *(a) Hidrografski zemljevid Hrvaške z označenim porečjem reke Sotle/Sutle. (b) Zemljevid porečja Sotle/Sutle s prikazanimi lokacijami hidroloških postaj Zelenjak (Hrvaška) in Rakovec (Slovenija) ter klimatološke postaje Bizeljsko (Slovenija). (c) Fotografija hidrološke postaje Zelenjak (Hrvaška). (d) Fotografija hidrološke postaje Rakovec (Slovenija). (e) Zračni posnetek reke Sotle/Sutle.*

It is possible that other relevant sources, not consulted in this review, contain further variations in these figures. Given the importance of this river as a border (transboundary) watercourse, Slovenian and Croatian authorities should urgently address this essential issue. The sustainable management of this basin and river could be seriously threatened by the emergence of dynamic and insufficiently controlled natural and anthropogenic changes. Despite the presence of a relatively large number of gauging stations in the Sotla/Sutla River basin, hydrological analyses have not sufficiently addressed the complex issues of past and, particularly, recent changes in the river's flow regime over time and space. Studies by Ulaga (2002), the FRISCO Project (2017), and Orešić and Filipčić (2024) have conducted hydrological analyses at several gauging stations within the basin. However, most analyses have focused on data from the two key stations, Zelenjak and Rakovec. Using datasets spanning different time periods, these studies generally concluded that there is a declining trend in annual flow rates. The underlying causes of this concerning trend have not been examined in detail.

Stojilković and Brečko Grubar (2024) examined the flow regimes of Slovenian rivers, including the Sutla at Rakovec. Similar investigations into the discharge characteristics of the Sotla/Sutla River were conducted in numerous earlier studies (Ilešič, 1947; Stele, 1987; Kolbezen, 1998; Hrvatin, 1998; Frantar and Hrvatin, 2005, 2008). These studies indicate that the Sotla/Sutla exhibits a moderate continental pluvial-nival regime, characterized by increased flows in late winter and spring due to snowmelt, and a secondary peak in late autumn associated with precipitation.

This study aims to document the long-term decline in the discharge of the transboundary Sotla/Sutla River and examine its possible connection to rising temperatures, particularly since the late 1990s. The analysis is conducted on an annual timescale, utilizing flow data from Zelenjak and Rakovec gauging stations, which hold the most complete and continuous record in the basin. These datasets offer the most reliable basis for detecting trends and drawing meaningful conclusions. Although six additional gauging stations exist along the Sotla/Sutla River and its tributaries, their records are either too short or are interrupted by significant gaps, limiting their utility for long-term analysis.

For this study, data on annual precipitation and mean annual air temperatures from the Bizeljsko climatological station will also be used, as it provides the only long-term, reliable meteorological record within the Sotla/Sutla River basin.

2. Materials

The data used in this study includes mean annual flows and annual minimum and maximum mean daily flows recorded at the Zelenjak hydrological station (Croatia) and Rakovec hydrological station (Slovenia).

Flow data for the Zelenjak station were obtained from the Croatian Meteorological and Hydrological Service, while data for the Rakovec station were retrieved from the Slovenian Environment Agency (ARSO) in Ljubljana.

At the Zelenjak station, records are available for the period 1958–2023 (66 years). The station is located 29.8 km upstream from the confluence with the Sava River, with a catchment area of 455 km² and a 'zero' point gauge is 162.46 m a.s.l.

At the Rakovec station, data cover the period 1926–2022, with a gap between 1942 and 1945, a total of 94 years of observations. The station is located 8 km from the Sava confluence, with a catchment area of 561.3 km² and a 'zero' point gauge altitude of 140.02 m a.s.l. Between 1965 and 2014, the Rakovec I station operated 70 m upstream, with a slightly lower 'zero' point of gauge (139.21 m a.s.l.) and a catchment area of 560.06 km². These values are based on official ARSO records.

For the climatological analyses, precipitation and air temperature data from the Bizeljsko station (Slovenia) (46°00′58″N, 15°41′46″E) were used, covering the period 1951–2024 (74 years). The station is situated at an elevation of 175 m a.s.l.

The natural characteristics of the Sotla/Sutla River basin have, to date, remained largely unaltered by anthropogenic interventions. The only substantial hydraulic modification was the construction of the Vonarje dam and associated reservoir. Located near the Slovenian settlement of Podčetrtek, the Vonarje dam was completed in 1980, with a structural height of 12 meters and a crest length of 120 meters. The impoundment created a reservoir approximately 6 km in length, covering a surface area of 195 hectares. The dam is situated in the upper portion of the Sotla/Sutla catchment. The crest elevation is 211.45 meters above sea level, while the base elevation is at 196 meters above sea level. The total storage volume of the reservoir is 12.4 × 10⁶ m³. The dam regulates a drainage area of 108.9 km², representing only the upper section of the catchment. As such, it exerts minimal influence on the hydrological regime at downstream gauging stations – Zelenjak (A = 455 km²; H = 162.46 m a.s.l.) and Rakovec (A = 561.3 km²; H = 139.21 m a.s.l.). Moreover, the reservoir was drained in 1988 and has not been returned to operational status since that time.

3. Methods

Linear regression lines were calculated to assess the strength of the relationship between dependent and independent variables. These regression models also helped determine linear trends in the time series of characteristic annual flows at the Zelenjak and Rakovec hydrological stations, as well as in annual precipitation and mean annual air temperatures at Bizeljsko. The linear regression equation is expressed as:

$$Y = (A \times X) + B \qquad (1)$$

where Y is the dependent variable and X is the independent variable, corresponding to the year in trend analyses. Coefficients A and B are calculated using the least squares method. The slope coefficient A indicates the average rate of an increase or decrease in the time series. A negative A implies a declining trend, while a positive A suggests an increasing trend. The coefficient of determination R^2 was calculated for each regression and reported. The value of R^2 represents the percentage of measured data that closely aligns with the fitted regression line. An R^2 of 0.70 suggests that 70% of the data variation aligns with the regression model (Davydenko et al., 2024).

To identify statistically significant shifts in the time series, the Rescaled Adjusted Partial Sums (RAPS) method was applied (Garbrecht & Fernandez, 1994; Bonacci, 2022; Bonacci et al., 2024). Unlike the Mann-Kendall (M-K) test, which is commonly used to detect the presence and direction of monotonic trends, the RAPS method allows for the exclusion of random variations and measurement errors within time series, enabling the clear detection of abrupt changes (spikes or declines) in the observed values. It is particularly effective for identifying sub-periods with statistically significant differences in mean values of the analyzed variable. The RAPS statistic is defined as:

$$RAPS_k = \Sigma_k ((Y_k - Y_N)/S_N) \quad (2)$$

where Y_k is the average value of the variable within subinterval k, Y_N denotes the mean across the full time series, S_N is the standard deviation of the entire series containing N data points, and k is the summation index ranging from 1 to N.

The F-test and t-test (McGhee, 1985) were used to evaluate statistical differences between mean values of consecutive sub-periods identified by the RAPS method. The F-test was applied to examine the equality of variances between two normally distributed populations (subsets), as a prerequisite for selecting the appropriate version of the t-test (assuming equal or unequal variances). The t-test was then used to quantitatively assess whether the mean values of the two time series subsets differ significantly. In both tests, a probability threshold of $p<0.01$ was chosen to accept the hypothesis that the mean values of the sub-periods are statistically significantly different.

For the available pairs of mean annual flows from Zelenjak (1958–2023) and Rakovec (1951–2022) with annual precipitation data from Bizeljsko, annual runoff coefficients were calculated. The runoff coefficient of a catchment represents the ratio of effective (net) precipitation to total (gross) precipitation over the catchment area serving as a key hydrological indicator in runoff analysis and water balance assessment (Bonacci, 2001).

To assess drought severity, values of the New Drought Index (NDI) were determined using mean annual air temperature T and annual precipitation P from Bizeljsko (1951–2024) (Bonacci and Bonacci, 2022; Bonacci et al., 2023).

The NDI is defined as:

$$NDI_i = [(P_i - P_{av})/SP] - [(T_i - T_{av})/ST] \quad (3)$$

where: P_i is the precipitation in year i, P_{av} is the average precipitation value of the analyzed time series, SP is the standard deviation of the analyzed precipitation time series, T_i is the mean annual air temperature in year i, T_{av} is the mean value of the analyzed air temperature time series, and ST is the standard deviation of the analyzed air temperature time series. The intensity categories of drought are classified based on *NDI* values. Mild droughts occur within the *NDI* range of 0 to −1.0, moderate droughts within −1.0 to −1.5, and severe droughts when the *NDI* value falls between −1.5 and −2.0. Extreme droughts occur when *NDI* values are lower than −2.0.

4. Analysis of Characteristic Annual Discharges at Two Hydrological Stations

4.1. Hydrological Station Zelenjak

Figure 2 presents the annual minimum mean daily discharges of the Sotla/Sutla River at the Zelenjak gauging station, categorized into two sub-periods using the RAPS method. In the first sub-period (1958–1987), the average annual minimum mean daily discharge at Zelenjak was 1.00 m^3/s, which is statistically significantly higher than in the more recent sub-period (1988–2023) where it declined to 0.68 m^3/s.

Figure 3 illustrates two subsets of mean annual discharges at the Zelenjak gauging station, also defined using the RAPS method. In the first sub-period (1958–1999), the average annual mean discharge at Zelenjak was 7.30 m^3/s, which is statistically significantly higher than in the more recent sub-period (2000–2023), where it declined to 5.60 m^3/s.

Figure 4 displays two subsets of the annual maximum mean daily discharges of the Sotla/Sutla River at the Zelenjak gauging station identified using the RAPS method.

In the first sub-period (1958–1987), the average annual maximum mean daily discharge was 106.3 m^3/s, which is statistically significantly higher than in the more recent sub-period (1988–2023), where it decreased to 67.0 m^3/s. The analysis indicates that in the recent period, all three characteristic annual discharge values at the Zelenjak station are significantly lower than in the previous sub-period.

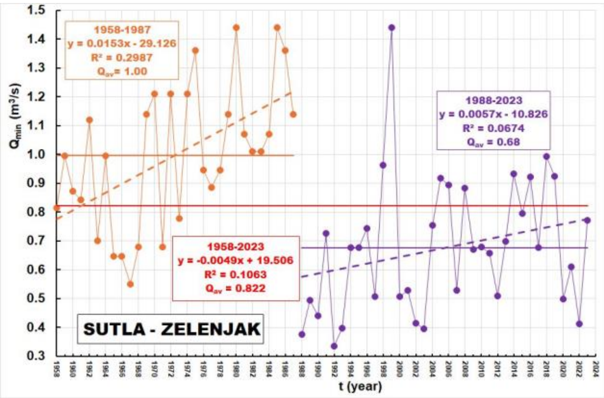

Figure 2: *Two subsets of annual minimum mean daily flows of the Sotla/Sutla River at the Zelenjak gauging station in the period 1958–2023.*

Slika 2: *Dva podniza letnih minimalnih srednjih dnevnih pretokov reke Sotle/Sutle na merilni postaji Zelenjak v obdobju 1958–2023.*

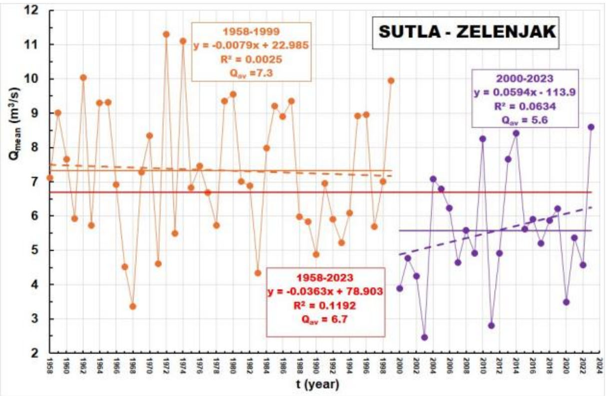

Figure 3: *Two subsets of mean annual flows of the Sotla/Sutla River at the Zelenjak gauging station in the period 1958–2023.*

Slika 3: *Dva podniza srednjih letnih pretokov reke Sotle/Sutle na merilni postaji Zelenjak v obdobju 1958–2023.*

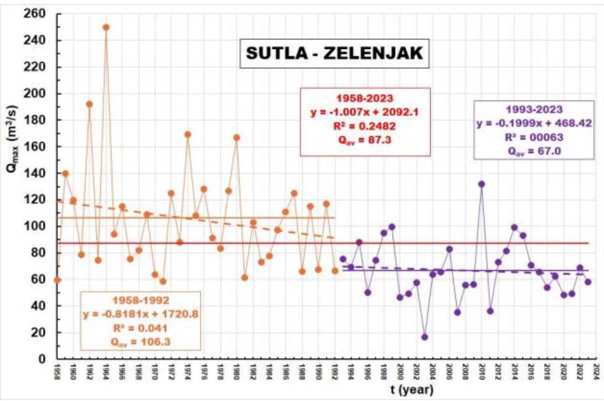

Figure 4: *Two subsets of annual maximum mean daily flows of the Sotla/Sutla River at the Zelenjak gauging station in the period 1958–2023.*

Slika 4: *Dva podniza letnih maksimalnih srednjih dnevnih pretokov reke Sotle/Sutle na merilni postaji Zelenjak v obdobju 1958–2023.*

4.2. Hydrological Station Rakovec

Figure 5 presents the series of annual minimum mean daily discharges of the Sotla/Sutla River at the Rakovec gauging station for the period 1926–2022 (excluding missing data for 1942–1945). The average value over the entire period is 0.837 m^3/s. Although no statistically significant trend is observed (R^2=0.0026) over the analyzed period, the values show considerable interannual variability.

Figure 6 illustrates two subsets of mean annual discharges of the Sotla/Sutla River at the Rakovec gauging station identified using the RAPS method.

In the first sub-period (1926–1999), the average annual mean discharge was 8.5 m^3/s, which is statistically significantly higher than in the more recent sub-period (2000–2022), where the average was 6.9 m^3/s.

Figure 7 displays three subsets of the annual maximum mean daily discharges of the Sotla/Sutla River at the Rakovec gauging station identified using the RAPS method. In the first sub-period (1926–1954), the average value was 51.0 m^3/s, which is statistically significantly lower than the average of 119.4 m^3/s observed during the 1955–1999 sub-period. In the recent sub-period (2000–2022), the average decreased to 77.4 m^3/s, indicating a statistically significant decline in annual maximum mean daily discharges.

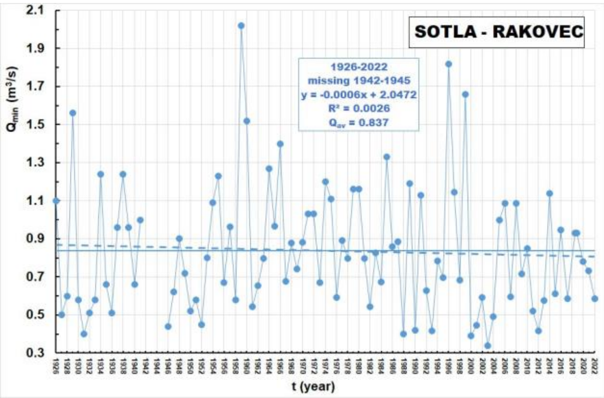

Figure 5: *Time series of annual minimum mean daily flows of the Sotla/Sutla River at the Rakovec gauging station in the period 1926–2022.*

Slika 5: *Časovna vrsta letnih minimalnih srednjih dnevnih pretokov reke Sotle/Sutle na merilni postaji Rakovec v obdobju 1926–2022.*

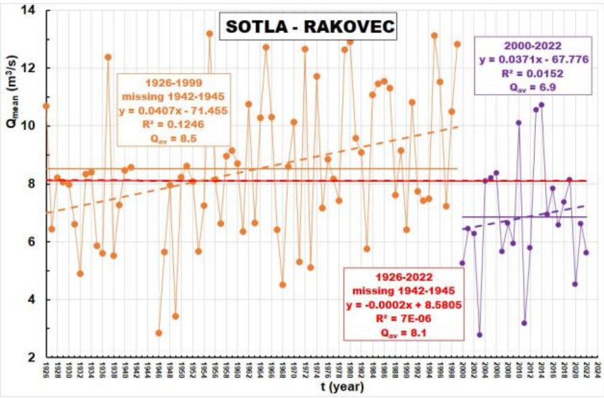

Figure 6: *Two subsets of mean annual flows of the Sotla/Sutla River at the Rakovec gauging station in the period 1926–2022.*

Slika 6: *Dva podniza srednjih letnih pretokov reke Sotle/Sutle na merilni postaji Rakovec v obdobju 1926–2022.*

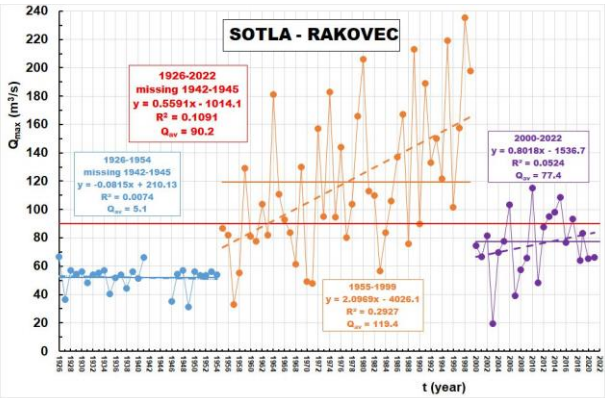

Figure 7: *Three subsets of annual maximum mean daily flows of the Sotla/Sutla River at the Rakovec gauging station in the period 1926–2022.*

Slika 7*: Trije podnizi letnih maksimalnih srednjih dnevnih pretokov reke Sotle/Sutle na merilni postaji Rakovec v obdobju 1926–2022.*

4.3. Comparison of results at the two hydrological stations

The relationship between the mean annual discharges of the Sotla/Sutla River at the Rakovec gauging station (ordinate axis) and the Zelenjak gauging station (abscissa axis) for the period 1958–2022 is shown in Figure 8.

The high coefficient of determination ($R^2 = 0.8739$) indicates a strong expected interdependence between the mean annual discharges at the downstream Rakovec station and those at the upstream Zelenjak station. The majority of values lie above the $Y = X$ line, confirming that Rakovec discharges are typically higher than those at Zelenjak. However, in 1973, the mean discharge at Zelenjak was approximately 5.5 m^3/s, while at Rakovec it was only about 5.0 m^3/s, which likely indicates an error in the flow estimation at one of the two stations.

The coefficient of determination for the relationship between the annual minimum mean daily discharges at the Rakovec and Zelenjak gauging stations for the period 1958–2022 was $R^2 = 0.2036$. The coefficient of determination for the annual maximum mean daily discharges at these stations for the same period was $R^2 = 0.3976$.

The analysis of discharge differences (ΔQ) between the two stations is presented in Figure 9, which includes ΔQ for annual minimum mean daily discharges (Figure 9A), mean annual discharges (Figure 9B), and annual maximum mean daily discharges (Figure 9C) of the Sotla/Sutla River at the Rakovec and Zelenjak stations for the period 1958–2022.

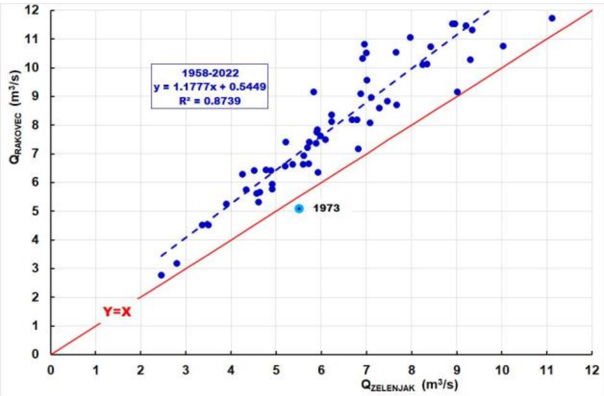

***Figure 8:** Relationship between mean annual flows of the Sotla/Sutla River at the Rakovec (ordinate axis) and Zelenjak (abscissa axis) gauging stations in the period 1958–2022.*

***Slika 8:** Razmerje med srednjimi letnimi pretoki reke Sotle/Sutle na merilnih postajah Rakovec (ordinatna os) in Zelenjak (abscisna os) v obdobju 1958–2022.*

In the series of differences in annual minimum mean daily discharges (Figure 9A), the average value is 0.085 m³/s, ranging from -0.468 m³/s (1982) to 1.12 m³/s (1959). No significant trend of increase or decrease is observed over time.

The series of differences in mean annual discharges (Figure 9B) reveals three sub-periods with statistically significant differences in average values. The overall average for the analyzed period (1958–2022) was 1.72 m³/s. In the first sub-period (1958–1978), the average value was 1.25 m³/s. In the second sub-period (1979–1999), it reached the highest value of 2.54 m³/s. In the most recent sub-period (2000–2022), it declined to 1.42 m³/s. The values range from -0.40 m³/s (1973) to 4.2 m³/s (1995). The series of differences in annual maximum mean daily discharges (Figure 9C) exhibits highly irregular variations over time. A significant increasing trend is present in the sub-period 1958–1999. However, no trend is observed in the recent sub-period (2000–2022). The average value is 11.0 m³/s, with a range from -17.0 m³/s (2010) to 28.2 m³/s (2000).

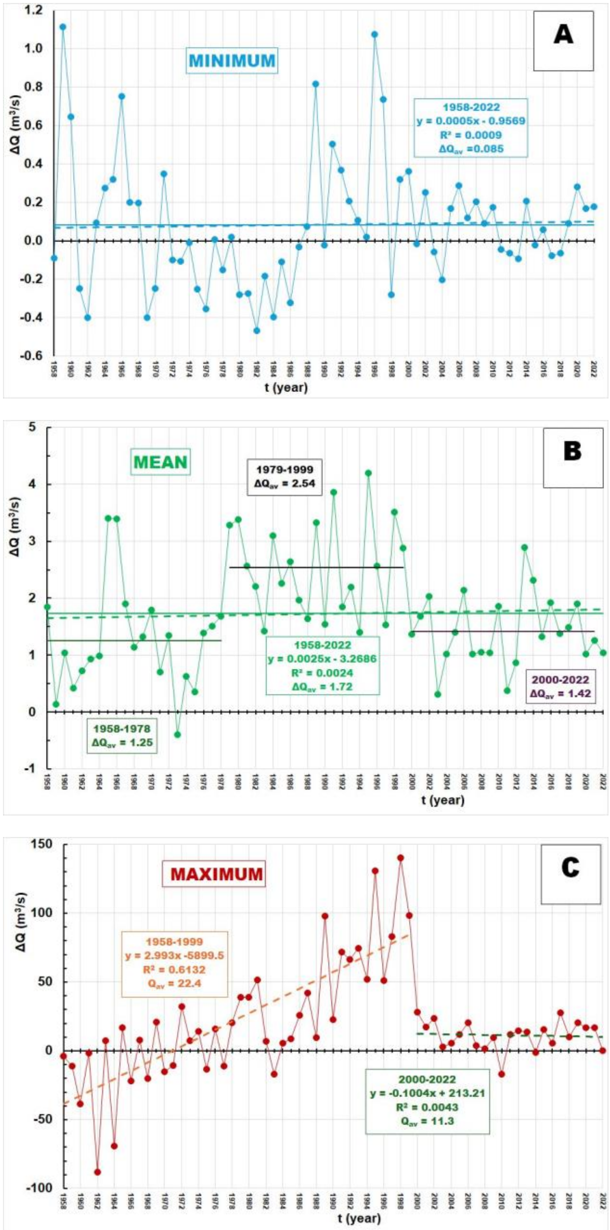

***Figure 9:** Time series of differences in annual minimum mean daily flows (Figure 9A), differences in mean annual flows (Figure 9B), and differences in annual maximum mean daily flows (Figure 9C) of the Sotla/Sutla River at the Rakovec and Zelenjak gauging stations in the period 1958–2022.*

***Slika 9:** Časovna vrsta razlik v letnih minimalnih srednjih dnevnih pretokih (slika 9A), razlik v srednjih letnih pretokih (slika 9B) in razlik v letnih maksimalnih srednjih dnevnih pretokih (slika 9C) reke Sotle/Sutle na merilnih postajah Rakovec in Zelenjak v obdobju 1958–2022.*

5. Climatological Station Bizeljsko

Figure 10 presents two sub-periods of the mean annual air temperatures at Bizeljsko for the period 1951–2024. The mean value in the first sub-period (1951–1997) was significantly lower – by as much as 1.54 °C – compared to the recent sub-period (1998–2024). Additionally, a pronounced increasing trend is observed in the recent sub-period.

Figure 11 shows two sub-periods of annual precipitation at Bizeljsko for the period 1951–2024. While the mean precipitation in the first sub-period (1951–1999) was slightly higher than in the recent sub-period (2000–2024), this difference is not statistically significant.

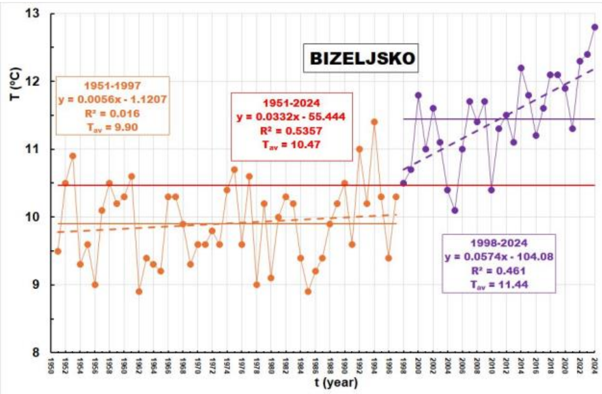

Figure 10: *Two subsets of mean annual air temperatures at Bizeljsko in the period 1951–2024.*

Slika 10: *Dva podniza srednjih letnih temperatur zraka na Bizeljskem v obdobju 1951–2024.*

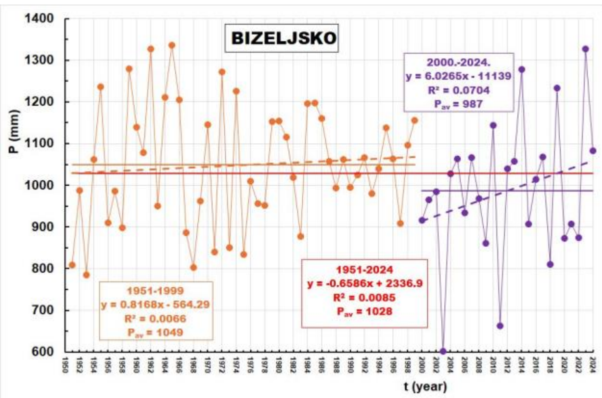

Figure 11: *Two subsets of annual precipitation at Bizeljsko in the period 1951–2024.*

Slika 11*: Dva podniza letne količine padavin na Bizeljskem v obdobju 1951–2024.*

Figure 12 presents the time series of the annual New Drought Index (NDI) values at Bizeljsko for the period 1951–2024, revealing a strong trend toward increased drought frequency over the past 25 years (2000–2024). Over the entire available period (1951–2024), a total of 38 drought events of all types were recorded, with 25 (66%) occurring in the recent period. Notably, between 1951 and 1999, only one extreme drought event was recorded, whereas in the past 25 years, there have been 9 such events.

The RAPS series of mean annual air temperatures (blue), annual precipitation (green), and the summarized series of annual New Drought Indices (NDI) (red) for Bizeljsko during the period 1951–2024 are presented in Figure 13. All three graphical representations confirm that, since 2000, there has been an intense and ongoing shift in climatic conditions, strongly influencing drought occurrences at the analyzed location and likely throughout the entire Sotla/Sutla River basin.

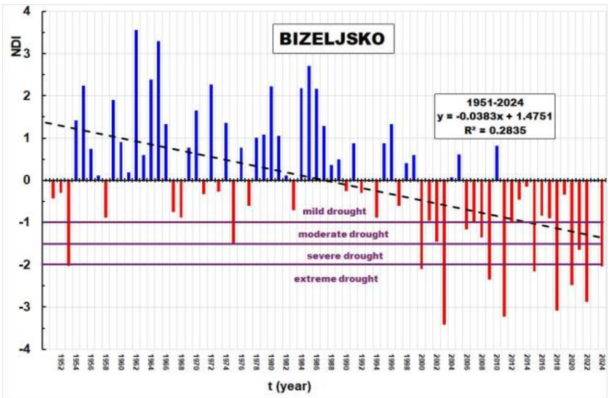

Figure 12*: Time series of annual New Drought Indices (NDI) at Bizeljsko in the period 1951–2024.*

Slika 12: *Časovna vrsta letnih vrednosti novega indeksa suše (NDI) na Bizeljskem v obdobju 1951–2024.*

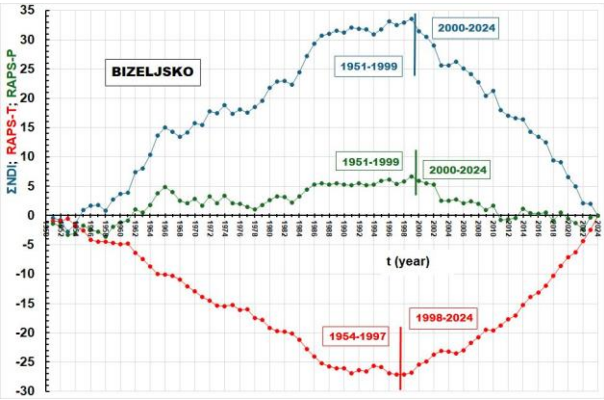

Figure 13: *Time series of annual RAPS values for mean temperatures (blue), annual precipitation (green), and a summary of annual New Drought Indices (NDI) (red) at Bizeljsko in the period 1951–2024.*

Slika 13: *Časovna vrsta letnih vrednosti RAPS za srednje temperature (modra barva), letno količino padavin (zelena barva) in vsoto letnih vrednosti novega indeksa suše (NDI) (rdeča barva) na Bizeljskem v obdobju 1951–2024.*

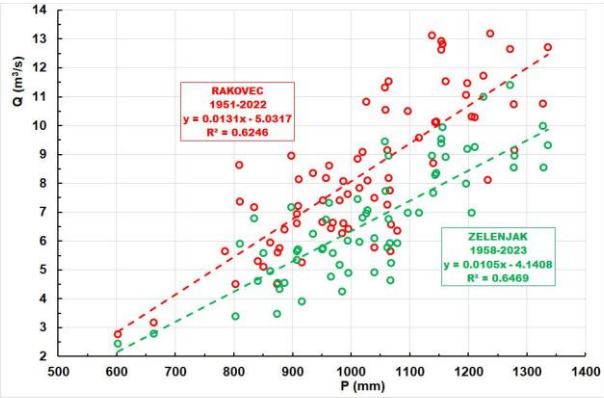

Figure 14: *Relationships between mean annual flows at the Zelenjak (blue) and Rakovec (red) gauging stations and annual precipitation at Bizeljsko.*

Slika 14: *Razmerje med srednjimi letnimi pretoki na merilnih postajah Zelenjak (modra barva) in Rakovec (rdeča barva) ter letno količino padavin na postaji Bizeljsko.*

Figure 14 illustrates the relationships between mean annual discharges at the Zelenjak (blue) and Rakovec (red) gauging stations and the annual precipitation at Bizeljsko.

The coefficients of determination are similar for both stations: $R^2 = 0.6469$ for Zelenjak and $R^2 = 0.6246$ for Rakovec. These values indicate a moderate correlation between the analyzed parameters.

6. Annual Runoff Coefficients

Figure 15 presents the time series of annual runoff coefficients for the Sotla/Sutla River at the Zelenjak gauging station (green) for the period 1958–2023 and at the Rakovec gauging station (red) for the period 1951–2022. At both gauging stations, the RAPS method identified two distinct sub-periods: the first extending up to and including 1999, and the second covering the recent sub-period starting in 2000.

At the Zelenjak station, during the first sub-period (1958–1999), the average runoff coefficient was $c = 0.474$, with values ranging from $c = 0.293$ (1968) to $c = 0.623$ (1972). In the recent sub-period (2000–2023), the average value was significantly lower at $c = 0.389$, with values ranging from $c = 0.276$ (2020) to $c = 0.507$ (2013).

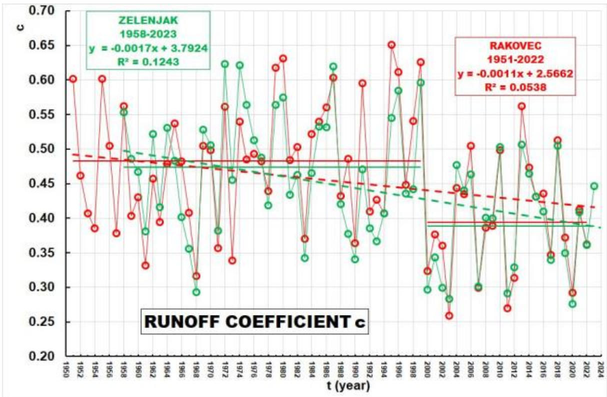

Figure 15*: Time series of annual runoff coefficients of the Sotla/Sutla River at the Zelenjak gauging station (green) in the period 1958–2023 and at the Rakovec gauging station (red) in the period 1951–2022.*

Slika 15: *Časovna vrsta letnih količnikov odtoka reke Sotle/Sutle na merilni postaji Zelenjak (zelena barva) v obdobju 1958–2023 in na merilni postaji Rakovec (rdeča barva) v obdobju 1951–2022.*

At the Rakovec station, during the first sub-period (1951–1999), the average runoff coefficient was c = 0.484, with values ranging from c = 0.317 (1968) to c = 0.651 (1995). In the recent sub-period (2000–2022), the average value was significantly lower at c = 0.394, with values ranging from c = 0.259 (2003) to c = 0.562 (2013).

7. Discussion

The analyses conducted in this study clearly underscore the complexity of hydrological and climatological processes in the Sotla/Sutla River basin. They also highlight the numerous challenges, potential inaccuracies, and uncertainties associated with data interpretation, which affect factors that complicate the formulation of reliable conclusions essential for water resource management in this vital transboundary river basin.

The results strongly suggest that substantial changes have occurred in the hydrological regime of the Sotla/Sutla River since approximately the year 2000. However, the extent to which these changes are driven by natural variability – primarily rising air temperatures – or by anthropogenic influences remains uncertain. Given the limitations of annual-scale analysis in resolving this issue, more detailed investigations at finer temporal resolutions are necessary. Such studies will necessitate enhanced collaboration among relevant institutions and experts from both Slovenia and Croatia.

A major constraint identified in this study is the limited reliability of available discharge data that are prone to measurement errors, particularly at flow extremes. The accuracy of flow measurements in open channels is influenced by numerous factors, and small rivers like the Sotla/Sutla are especially vulnerable to these uncertainties. This concern becomes even more significant when analyzing long-term discharge series, as earlier measurement techniques differ considerably from modern methods, such as Acoustic Doppler Current Profilers (ADCPs). Although ADCPs have improved the frequency and flexibility of measurements, especially during high-flow events, their accuracy remains comparable to that of traditional current meter methods and is still subject to measurement errors.

The development of reliable stage-discharge rating curves is a fundamental prerequisite for accurate hydrological analysis and, consequently, for informed decision-making in water resource management. However, maintaining precise rating curves over extended periods is challenging due to continuous changes in the watershed and river channel morphology – a factor likely influencing the Sotla/Sutla River as well. In fact, defining reliable rating curves is often more complex than conducting the discharge measurements themselves. The relationship between water level and discharge depends on the evolving composition and geometry of the riverbed, shaped by both natural dynamics and anthropogenic influences.

The relationship between water level and discharge is influenced by numerous factors, including non-stationary flow conditions, ice formation, sediment deposition, bank and bed instability, and human interventions. While this relationship is inherently stochastic, engineering and hydrotechnical applications require a well-defined analytical function.

Due to challenges in measuring extreme flows, rating curves often require extrapolation beyond the highest or lowest observed water levels. However, such extrapolation is only viable under simple conditions and becomes increasingly uncertain when significant alterations in channel geometry, floodplain connectivity, or roughness coefficients occur at higher stages. Flow measurements during high-water events are rare, hazardous, or even unfeasible, particularly for small watercourses with tendencies towards flash floods, such as the Sotla/Sutla River.

Furthermore, rating curves typically assume steady-state flow conditions, overlooking the hysteresis effects that occur in the stage-discharge relationship during flood wave propagation. This introduces additional uncertainty in estimating annual peak discharges, as the shape of the hysteresis loop varies for each flood event. As a result, maximum annual discharges should be interpreted with caution, and official hydrological data must be evaluated carefully. It has been precisely these challenges that have significantly influenced hydrologists in their efforts to define accurate rating curves for the Sotla/Sutla River.

8. Conclusions and Recommendations for Future Research

This study highlights the urgent need for strengthened and sustained cooperation between the relevant institutions of Slovenia and Croatia in addressing the hydrological challenges of the Sotla/Sutla River – a relatively small, but ecologically and strategically significant transboundary river.

Our analyses revealed consistent and difficult-to-reconcile discrepancies between discharge data reported by the two countries' official institutions. A distinct decline in mean annual flows has been observed since approximately 2000, coinciding with the onset of an intensified warming trend beginning in 1998. This temporal alignment strongly suggests that rising air temperatures have played a major role in driving the observed reduction in discharge.

Given the projected continuation of regional warming in the coming decades, further reductions in river flow are highly likely. These findings underscore the necessity of a more systematic and coordinated bilateral approach to water resource management in the Sotla/Sutla basin. Strengthened cooperation is essential not only for effective adaptation to ongoing climate change but also for enhancing transparency and building mutual trust in the exchange of hydrological data, thereby minimizing the potential for misunderstandings between two otherwise amicable neighboring countries.

Despite successful collaboration in other environmental domains, the continued presence of unresolved discrepancies in fundamental hydrological and hydromorphological data remains concerning. Addressing these gaps through joint monitoring, harmonization of datasets, and collaborative interpretation should be prioritized in future bilateral initiatives.

Acknowledgments

This research was partially funded by the project KK.01.1.1.02.0027, co-financed by the Government of Croatia and the European Union through the European Regional Development Fund - the Competitiveness and Cohesion Operational Programme.

CRediT authorship contribution statement

Conceptualization, O.B.; methodology, O.B. and T.R.B.; software, O.B. and A.Z.C.; validation, A.Z.C. and T.R.B.; formal analysis, O.B. and T.R.B.; investigation, O.B. and A.Z.C.; data curation, O.B. and A.Z.C.; writing – original draft preparation, O.B.; writing – review and editing, A.Z.C.; visualization, O.B. and A.Z.C.; supervision, T.R.B.; project administration, T.R.B.

Data availability

The data presented in this paper are available from the corresponding author upon request.

Declaration of interest

The authors declare no conflict of interest.

References

Bonacci, O. (2001). Monthly and annual effective infiltration coefficients in Dinaric karst: example of the Gradole karst spring catchment. *Hydrological Sciences Journal* **46(2)**, 287-299. https://doi.org/10.1080/02626660109492822.

Bonacci, O. (2022). What is above average air temperature!? *Theoretical and Applied Climatology* **149(3-4)**, 1-17. https://doi.org/10.1007/s00704-022-04144-y.

Bonacci, O.; Bonacci, D. (2022). Prijedlog nove metode za analizu suša. *Hrvatske Vode* **30(119)**, 1-16.

Bonacci, O.; Bonacci, D.; Roje-Bonacci, T.; Vrsalović, A. (2023). Proposal of a new method for drought analysis. *Journal of Hydrology and Hydromechanics* **71 (1)**, 100-110. https://doi.org/10.2478/johh-2022-0030.

Bonacci, O.; Žaknić-Ćatović, A.; Roje-Bonacci, T. (2024). Prominent increase in air temperatures on two small Mediterranean islands, Lastovo and Lošinj, since

1998 and its effect on the frequency of extreme droughts. *Water* **16(3175)**. https://doi.org/10.3390/w16223175.

Čosić-Flajsig, G.; Karleuša, B.; Glavan, M. (2021). Integrated water quality management model for the rural transboundary river basin – a case study of the Sutla/Sotla River. *Water* **13**, 2569. https://doi.org/10.3390/w13182569.

Davydenko, N.; Wasilewska, N.; Titenko, Z.; Wasilewski, M. (2024). Substantiation of the Risk Neutralization Mechanism in the Financial Security Management of Agricultural Enterprises. *Sustainability* **16**, 1159. https://doi.org/10.3390/su16031159.

Dragun, Z.; Kapetanović, D.; Raspor, B.; Teskeredžić, E. (2011). Water quality of medium size watercourse under baseflow conditions: the case study of river Sutla in Croatia. *Ambio - A Journal of the Human Environment* **40 (4)**, 391-407. https://doi.org/10.1007/s13280-010-0119-z.

Frantar, P.; Hrvatin, M. (2005). Discharge regimes in Slovenia from 1971 to 2000. *Geografski Vestnik* **77-2**.

Frantar, P.; Hrvatin, M. (2008). Discharge regimes. In: *Water Balance of Slovenia 1971–2000*. Ministry for Environment and Spatial Planning – Environmental Agency of the Republic of Slovenia.

FRISCO Project. (n.d.). Porečja – Sotla. Retrieved February 26, 2025, from https://frisco-project-eu/sl/porecja/sotla/.

Enciklopedija.hr. (n.d.). Sutla. Retrieved February 26, 2025, from https://www.enciklopedija.hr/clanak/sutla.

Garbrecht, J.; Fernandez, G. P. (1994). Visualization of trends and fluctuations in climatic records. *Water Resources Bulletin* **30(2)**, 297–306. https://doi.org/10.1111/j.1752-1688.1994.tb03292.x.

Hrvatin, M. (1998). Discharge regimes in Slovenia. *Geografski zbornik*, **38**, 59-87.

Ilešič, S. (1947). Rečni režimi v Jugoslaviji. *Geografski Vestnik* **19**.

Kolbezen, M. (1998). Rečni režimi. In: *Površinski vodotoki in vodna bilanca Slovenije*. Ministrstvo za okolje in prostor. Hidrometeorološki zavod Republike Slovenije.

McGhee, J. W. (1985). *Introductory statistics*. West Publishing Company, St Paul and New York.

Orešić, D.; Filipčić, A. (2024). Promjene protočnih režima najvećih savskih i dravskih pritoka u Hrvatskom Zagorju i Gornjoj Podravini 1961– 2020. *Podravina*, **23(45)**, 33-52.

Prah, K.; Lisec, A.; Lisec, A. (2013). Digital spatial data as support for river basin management: The case of Sotla river basin. *Spatium* **29**, 59-67. https://doi.org/10.2298/SPAT1329059P.

Projekt FRISCO1 (2017). FRISCO1 (Cross-Border Harmonised Slovenian-Croatian Flood Risk Reduction 1 – Non Structural Measures). EU Cooperation Programme INTERREG V-A Slovenia–Croatia; 2014–2020. https://frisco-project.eu.

Stele, A. (1987). Rečni režimi v Sloveniji. In: *Publikacija ob 40-letnici zavoda*. Hidrometeorološki zavod SR Slovenije.

Stojilković, B.; Brečko Grubar, V. (2024). Discharge regimes of Slovenian rivers: 1991–2020. *Acta Geographica Slovenica* **64(3)**, 7-31. https://doi.org/10.3986/AGS.13654.

Ulaga, F. (2002). Trendi spreminjanja pretokov slovenskih rek. *Dela*, **18**, 93-114, https://doi.org/10.4312/dela.18.93-114.

Žiger, Z.; Bognar, A. (2007). Geomorfološka obilježja gornjeg toka rijeke Sutle. *Hrvatski Geografski Glasnik*. **69(1)**, 25-39.