



Isotopic composition of hydrogen and oxygen in precipitation at the station Ljubljana (Reaktor), Slovenia: period 2011–2024

Izotopska sestava vodika in kisika v padavinah na postaji Ljubljana (Reaktor), Slovenija: obdobje 2011–2024

Jan GAČNIK*, Marko ŠTOK, Klara ŽAGAR & Polona VREČA

Department of Environmental Sciences, Jožef Stefan Institute, Jamova cesta 39, 1000 Ljubljana, Slovenia,

*corresponding author: jan.gacnik@ijs.si

Prejeto / Received 11. 2. 2025; Sprejeto / Accepted 8. 6. 2026; Objavljeno na spletu / Published online 24. 7. 2026

Key words: precipitation, hydrogen isotopes, oxygen isotopes, monitoring, temporal trends, Slovenia

Ključne besede: padavine, izotopi vodika, izotopi kisika, monitoring, časovni trendi, Slovenija

Abstract

Long-term monitoring of the isotopic composition of precipitation is essential for obtaining insights into hydrological processes. This study presents an updated and expanded dataset of stable isotopic composition of hydrogen ($\delta^2\text{H}$) and oxygen ($\delta^{18}\text{O}$), deuterium excess (d-excess), and tritium activity concentration ($A(^3\text{H})$) in monthly composite precipitation samples collected at the SLONIP station Ljubljana (Reaktor), Slovenia for the period 2011–2024. The dataset is evaluated together with meteorological observations for Ljubljana (Bežigrad) and Ljubljana (Hrastje) national stations to assess temporal variability and is compared with previously published data for the 2007–2010 period.

The mean precipitation-weighted values for 2011–2024 were -8.41‰ for $\delta^{18}\text{O}$, -56.1‰ for $\delta^2\text{H}$, 11.1‰ for d-excess, and 6.7 TU for $A(^3\text{H})$, with all parameters except $A(^3\text{H})$ showing an increase compared to 2007–2010 period. The increase of $\delta^{18}\text{O}$ and $\delta^2\text{H}$ is consistent with rising air temperatures, whereas the decrease in $A(^3\text{H})$ reflects the radioactive decay of ^3H originating from atmospheric nuclear weapons testing. Temporal trends reveal a seasonal cycle of $\delta^2\text{H}$ and $\delta^{18}\text{O}$, with summer maxima and winter minima, strongly correlated with air temperature ($r = 0.75$ for $\delta^2\text{H}$ and $r = 0.78$ for $\delta^{18}\text{O}$). The local meteoric water line (LMWL), $\delta^2\text{H} = (7.76 \pm 0.07) \delta^{18}\text{O} + (9.11 \pm 0.65)$, has a lower slope and intercept for the period 2011–2024 than for the period 2007–2010. Precipitation amount does not substantially influence mean isotopic values, although isotopic extremes were typically associated with low precipitation events. No statistically significant differences were found between precipitation-weighted means of $\delta^2\text{H}$, $\delta^{18}\text{O}$, d-excess, and $A(^3\text{H})$, calculated using precipitation amounts from the Ljubljana (Bežigrad) and Ljubljana (Reaktor) stations. Continued long-term monitoring within the SLONIP programme is essential for statistically robust climate and hydrological assessments in Slovenia and the wider geographical region.

Izvilleček

Dolgoročno spremljanje izotopske sestave padavin je ključno za pridobivanje informacij o hidroloških procesih. Ta študija predstavlja posodobljen in razširjen niz podatkov o izotopski sestavi vodika ($\delta^2\text{H}$) in kisika ($\delta^{18}\text{O}$), devterijevem presežku (d-excess), ter koncentracijah aktivnosti tritija $A(^3\text{H})$ v mesečnih kompozitih padavin, zbranih na SLONIP postaji Ljubljana (Reaktor), Slovenija v obdobju 2011–2024. Podatkovni niz smo analizirali skupaj z meteorološkimi podatki iz državnih postaj Ljubljana (Bežigrad) in Ljubljana (Hrastje), z namenom oceniti časovne spremembe in primerjati rezultate z rezultati za obdobje 2007–2010.

Srednje padavinsko-tehtane vrednosti za izotopsko sestavo padavin v obdobju 2011–2024 znašajo: $-8,41\text{‰}$ za $\delta^{18}\text{O}$, $-56,1\text{‰}$ za $\delta^2\text{H}$, $11,1\text{‰}$ za d-excess ter $6,7\text{ TU}$ za $A(^3\text{H})$. Vse vrednosti izotopskih parametrov razen $A(^3\text{H})$ so višje v primerjavi z obdobjem 2007–2010. Višje vrednosti $\delta^{18}\text{O}$ in $\delta^2\text{H}$ so skladne z naraščajočimi temperaturami zraka, medtem ko je nižja vrednost $A(^3\text{H})$ skladna z radioaktivnim razpadom ^3H , nastalega pri zračnih jedrskih poskusih. Pri časovnih trendih je razviden sezonski cikel $\delta^2\text{H}$ in $\delta^{18}\text{O}$, s poletnimi maksimumi ter zimskimi minimumi, močno koreliranimi z temperaturo zraka ($r = 0.75$ za $\delta^2\text{H}$ in $r = 0.78$ za $\delta^{18}\text{O}$). Lokalna meteorna premica (LMWL), $\delta^2\text{H} = (7.76 \pm 0.07) \delta^{18}\text{O} + (9.11 \pm 0.65)$, ima za obdobje 2011–2024 nižji naklon ter začetno vrednost kot za obdobje 2007–2010. Količina padavin nima znatnega vpliva na srednje izotopske vrednosti, čeprav so ekstremne vrednosti izotopske sestave pogosto povezane z nizkimi količinami padavin. Med padavinsko-uteženimi povprečji $\delta^2\text{H}$, $\delta^{18}\text{O}$, d-excess in $A(^3\text{H})$, izračunanimi z uporabo količin padavin na postajah Ljubljana (Bežigrad) in Ljubljana (Reaktor), ni bilo statistično značilnih razlik. Nadaljnje dolgoročno spremljanje v okviru programa SLONIP je bistvenega pomena za statistično robustne podnebne in hidrološke ocene v Sloveniji in širši geografski regiji.

Introduction

Precipitation is the primary source of surface water and groundwater, and represents an integral part of the hydrological cycle. Thus, understanding of the dynamics between different components of the hydrological cycle is crucial for sustainable water resource management (Schirmer et al., 2013). Water fluxes between atmosphere and surface water reservoirs are affected by climatic processes, some of which can be traced and studied through the use of stable hydrogen ($\delta^2\text{H}$) and oxygen ($\delta^{18}\text{O}$) isotopes, and tritium activity concentration ($A(^3\text{H})$) in precipitation (Gourcy et al., 2005).

Multidecadal datasets of hydrogen and oxygen isotopes in precipitation are needed in order to detect long-term climatic shifts that can inform national strategic planning, particularly in the context of rising air temperatures and changing precipitation patterns (Gačnik et al., 2026). Such datasets are generally facilitated by international or national-based precipitation monitoring networks, such as the Global Network of Isotopes in Precipitation (GNIP) (International Atomic Energy Agency & World Meteorological Organization, n.d.), the Austrian Network for Isotopes in Precipitation (ANIP) (Bundesministerium für Land-und Forstwirtschaft, n.d.; Hager & Foelsche, 2015), the Swiss National Network for the Observation of Isotopes in the Water Cycle (NISOT) (Schürch et al., 2003), Slovenian Network of Isotopes in Precipitation (SLONIP) (Jožef Stefan Institute, 2020; Vreča et al., 2022), and more.

Since 2014, the precipitation isotope dataset for Ljubljana (Reaktor) has been used in numerous studies related to the water cycle. These studies cover a wide range of topics, including precipitation (Brenčič et al., 2015; Filipović et al., 2022; Gačnik et al., 2026; Hatvani et al., 2021, 2023; Hughes & Crawford, 2012; Kern, Erdelyi, et al., 2020; Kern, Hatvani, et al., 2020; Krajcar Bronić, Barešić, Borković, et al., 2020; Nagode, Pavšek, et al., 2022; Vreča et al., 2022, 2023; Vreča & Pavšek, 2022), caves (Domínguez-Villar et al., 2018) and ice caves (Carey et al., 2019; Mulec et al., 2021; Racine et al., 2022; Smith et al., 2023), thermal springs (Serianz et al., 2020; Winter, 2019), surface waters, groundwater and groundwater discharges (Brkić et al., 2020, 2021; Kanduč et al., 2019; Ogrinc et al., 2018; Parlov et al., 2019; Rusjan et al., 2019; Torkar et al., 2016; Trček & Mesarec, 2023), surface water (Nagode, Pavšek, et al., 2022; Torkar et al., 2016), water supply systems (Nagode, Kanduč, et al., 2022; Žagar et al., 2024), general hydrology (Bezjak et al., 2017; Nagode et al., 2020; Vreča, Kanduč, et al., 2017; Vreča & Malenšek, 2016) and archaeology

(Leskovar et al., 2025). Lately, the long-term stable isotope record of precipitation in Ljubljana was explored in detail and the results imply an accelerating, exponential-like isotopic response to climate warming in last decade that has already propagated into the water cycle (Gačnik et al., 2026).

This study aims to update and expand the isotopic record of precipitation for Ljubljana (Reaktor) by presenting new data and their evaluation covering the period 2011–2024. The objectives are to i) characterize the temporal variations in stable isotopic composition ($\delta^2\text{H}$, $\delta^{18}\text{O}$, and d-excess) and $A(^3\text{H})$, ii) compare the new data with previously published results for 2007–2010, and iii) evaluate the relation between isotopic composition, temperature, and precipitation to better understand climatic and hydrological influences on precipitation in Ljubljana.

Materials and methods

Sampling

Monthly composite precipitation samples were collected at SLONIP research station Ljubljana (Reaktor) (Fig. 1, WGS84: 46.094612° N, 14.597046° E, 282 m a.s.l.) from January 2011 to December 2024 by the staff of the Department of Environmental Sciences (O-2) of the Jožef Stefan Institute (JSI). Samples were collected from a precipitation gauge as soon as possible after a precipitation event. The volume of collected precipitation was measured in the laboratory and the sample was poured into a 5-litre plastic bottle with a tight-fitting cap.

After bringing the samples to the laboratory the impurities (e.g. dust, particles) were removed from the sample by filtration through Black Ribbon filter paper before taking aliquots for different isotope analyses. A 30- or 50-mL borosilicate glass bottles provided by International Atomic Energy Agency (IAEA) were filled for the stable isotope analysis of hydrogen and oxygen and the rest of the water was transferred to 0.5- or 1-L high density polyethylene (HDPE) bottles provided by IAEA for tritium activity concentration analysis.

During the sampling period, the amount of water collected in December 2016 (only traces, amount not determined) was insufficient for all isotope analysis, while amount of water collected in November 2011, December 2015, December 2018, January and April 2020, and March 2022 was insufficient for tritium activity concentration analyses. In August 2015, the tube that connects the precipitation collector with the sampling bottle was blocked.

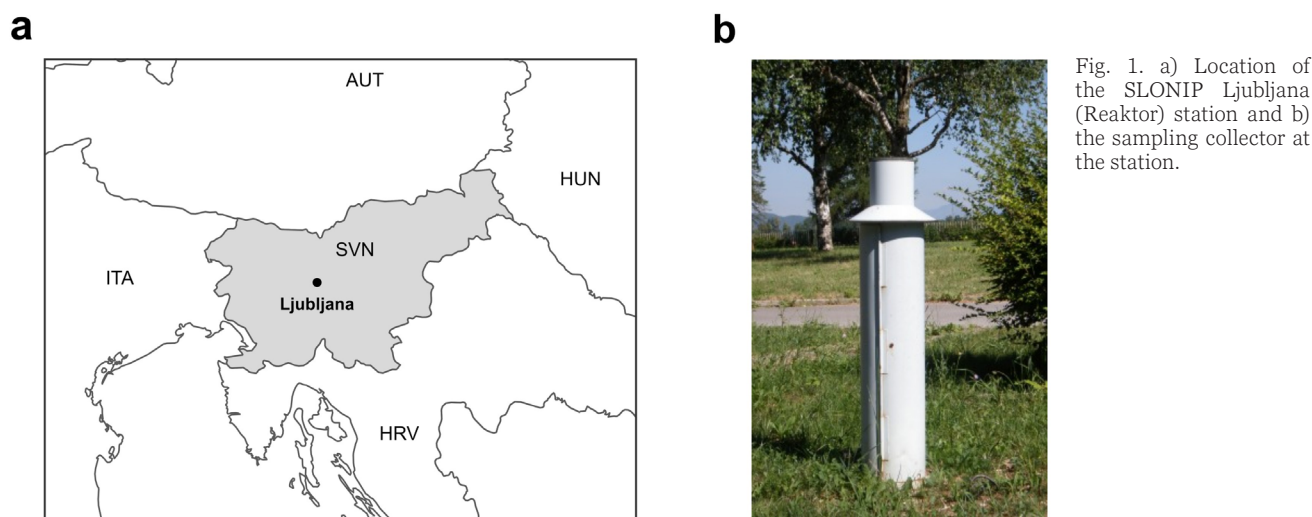


Fig. 1. a) Location of the SLONIP Ljubljana (Reaktor) station and b) the sampling collector at the station.

Table 1. List of analytical methods used and laboratories where isotopic composition of precipitation in Ljubljana was determined since 1981. DI – dual inlet; CF – continuous flow; IRMS – isotope ratio mass spectrometer; CO₂ equil. – water-CO₂ equilibration technique; Zn red. to H₂ – zinc reduction method; Cr red. to H₂ – chromium reduction method; Pt red. to H₂ – platinum reduction method; OA-ICOS – off-axis integrated cavity output laser absorption spectroscopy; LSC-EE – electrolytic enrichment liquid scintillation counting; JSI – Jožef Stefan Institute; RBI – Ruđer Bošković Institute, Zagreb, Croatia; IAEA – International Atomic Energy Agency; JR – Joanneum Research, Graz, Austria.

Station name	Period	Analytical methods and laboratories			References
		$\delta^{18}\text{O}$	$\delta^2\text{H}$	A(³ H)	
Ljubljana–Bežigrad	1981–1992	DI IRMS CO ₂ equil. Varian MAT 250 (JSI)	DI IRMS Zn red. to H ₂ Varian MAT 250 (JSI)	GPC (RBI)	Pezdič (1999, 2003), Vreča et al. (2008)
Ljubljana–IJS	1993–1997	DI IRMS CO ₂ equil. Varian MAT 250 (JSI)	DI IRMS Zn red. to H ₂ Varian MAT 250 (JSI)	GPC (RBI)	Pezdič (1999, 2003), Vreča et al. (2008)
Ljubljana–Reaktor	1998–2000	DI IRMS CO ₂ equil. Varian MAT 250 (JSI)	DI IRMS Cr red. to H ₂ Varian MAT 250 (JSI)	GPC (RBI)	Pezdič (1999, 2003), Vreča et al. (2008)
Ljubljana–Reaktor	2000–2003	DI IRMS CO ₂ equil. Varian MAT 250 (JSI)	DI IRMS Cr red. to H ₂ Varian MAT 250 (JSI)	GPC (RBI) LSC-EE (IAEA)	Vreča et al. (2008)
Ljubljana–Reaktor	2004–2006	DI IRMS CO ₂ equil. Finnigan MAT DELTA ^{plus} (JR)	CF IRMS Cr red. to H ₂ Finnigan DELTA ^{plus} XP (JR)	GPC (RBI)	Vreča et al. (2008)
Ljubljana–Reaktor	2007–2010	DI IRMS CO ₂ equil. Finnigan MAT DELTA ^{plus} (JR) or CF IRMS CO ₂ equil. IsoPrime with Multiflow Bio (JSI)	CF IRMS Cr red. to H ₂ Finnigan DELTA ^{plus} XP (JR)	GPC (RBI) LSC-EE Quantulus 1220 (RBI) or LSC-EE TriCarb 3170 TR/SL (JSI)	Vreča et al. (2014)
Ljubljana–Reaktor	2011–2015	CF IRMS CO ₂ equil. IsoPrime with Multiflow Bio or DI IRMS CO ₂ equil. Finnigan MAT DELTA ^{plus} (JSI) or OA-ICOS (IAEA)	CF IRMS Cr red. to H ₂ Finnigan DELTA ^{plus} XP (JR) or DI IRMS Pt red. to H ₂ Finnigan MAT DELTA ^{plus} (JSI) or or OA-ICOS (IAEA)	LSC-EE Quantulus 1220 (RBI) or LSC-EE TriCarb 3170 TR/SL (JSI)	Gačnik et al. (2026) and this paper
Ljubljana–Reaktor	2016–	DI IRMS CO ₂ equil. Finnigan MAT DELTA ^{plus} (JSI)	DI IRMS Pt red. to H ₂ Finnigan MAT DELTA ^{plus} (JSI)	LSC-EE TriCarb 3170 TR/SL or Quantulus 1220 (JSI)	Gačnik et al. (2026) and this paper

Stable isotope analysis ($\delta^2\text{H}$ and $\delta^{18}\text{O}$)

Complete list of used analytical methods and laboratories for determination of $\delta^2\text{H}$ and $\delta^{18}\text{O}$ in precipitation is shown in Table 1.

During the period 2011–2015, the capabilities for determination of isotopic composition of hydrogen at JSI were limited, therefore, we cooperated with two foreign water isotope laboratories operating in Austria, one at Joanneum Research (JR) in Graz and the other at IAEA in Vienna.

The isotopic composition of hydrogen ($\delta^2\text{H}$) in samples collected between January 2011 and June 2011 was determined on a CF IRMS Finnigan DELTAplus XP with a HEKAtech high-temperature oven, by reduction of water over hot chromium (Morrison et al., 2001) at JR (Vreča et al., 2014). The typical uncertainty reported as the long-term standard deviation of a laboratory reference material was ± 1 ‰ for $\delta^2\text{H}$ (Vreča, Štok, et al., 2017).

The isotopic composition of oxygen ($\delta^{18}\text{O}$) in samples collected between January 2011 and March 2015 was determined on a continuous flow isotope ratio mass spectrometer (CF IRMS) IsoPrime with MultiFlow-Bio module at the JSI by means of water- CO_2 equilibration technique (Epstein & Mayeda, 1953). All samples were measured as independent duplicates and the typical uncertainty reported as the long-term standard deviation of a laboratory reference material was 0.07 ‰ for $\delta^{18}\text{O}$ (Vreča, Štok, et al., 2017).

Since 2016 the $\delta^2\text{H}$ and $\delta^{18}\text{O}$ were analysed at the JSI also according to the water- H_2 (platinum – Pt) and water- CO_2 equilibration technique (Avak & Brand, 1995; Coplen et al., 1991; Gourcy et al., 2005) on a dual inlet isotope ratio mass spectrometer (DI IRMS) Finnigan MAT DELTA plus with automated H_2 - H_2O and CO_2 - H_2O equilibrator HDO-EQ48 (Lancaster et al., 2025; Vreča et al., 2022, 2024). All samples were measured as independent duplicates and the uncertainties were estimated to be less than 1 ‰ and 0.05 ‰ for $\delta^2\text{H}$ and $\delta^{18}\text{O}$ (Vreča et al., 2022). More than half of samples (31 of 60) collected during the period 2011–2015 were remeasured by this technique (Vreča, Štok, et al., 2017).

Samples collected between January 2013 and December 2015 were sent also to Isotope Hydrology Laboratory (IHL) at IAEA where $\delta^2\text{H}$ and $\delta^{18}\text{O}$ were determined by off-axis integrated cavity output laser spectroscopy (OA-ICOS, Los Gatos Research, Mountain View CA, United States of America). Samples were run in duplicate with each analysis run conducted on a different day and on a different instrument. The analytical protocol was adapted from Wassenaar et al. (2014). Selected

samples were repeated on a dual-inlet isotope ratio mass spectrometer (Thermo Finnigan Delta Plus, Bremen, Germany) following equilibration with H_2 or CO_2 gases respectively in a custom-built equilibration unit. The typical uncertainty reported as the long-term standard deviation of a control sample amounts to 0.5 ‰ for $\delta^2\text{H}$ and 0.08 ‰ for $\delta^{18}\text{O}$ (S. Terzer, personal communication).

The collected stable hydrogen ($\delta^2\text{H}$) and oxygen ($\delta^{18}\text{O}$) isotope data are expressed in standard δ notation, as per mil (‰) deviation of the sample (sp) from the standard (st) as:

$$\delta^y\text{X (‰)} = \left(\frac{R_{sp}}{R_{st}} - 1 \right) \times 1000 \quad (1)$$

where ^yX is ^2H or ^{18}O , R_{sp} and R_{st} is $^2\text{H}/^1\text{H}$ or $^{18}\text{O}/^{16}\text{O}$ ratio of the sample and the standard, respectively (Coplen, 1995). Measurements were carried out together with laboratory reference materials (LRM) that are calibrated periodically against IAEA calibration standards to VSMOW/SLAP international reference scale (International Atomic Energy Agency & World Meteorological Organization, n.d.; Lancaster et al., 2025; Vreča et al., 2022, 2024). Results were normalised to VSMOW/SLAP by the LIMS (Laboratory Information Management System for Light Stable Isotopes) programme and the final $\delta^2\text{H}$ and $\delta^{18}\text{O}$ data are rounded to 1 decimal and 2 decimals, respectively (Gačnik et al., 2026).

Tritium activity concentration – $A(^3\text{H})$

Complete list of used analytical methods and laboratories for determination of $A(^3\text{H})$ in precipitation is shown in Table 1.

Tritium activity concentration - $A(^3\text{H})$ - in samples collected between January 2011 and June 2012 was determined at the Tritium Laboratory of the Department of Experimental Physics of the Ruđer Bošković Institute (RBI) in Zagreb. Samples were measured by the liquid scintillation counting technique following electrolytic enrichment (LSC-EE) using ultra-low-level liquid scintillation counter Quantulus 1220 (Wallac, PerkinElmer). The limit of detection of the method is 0.3 to 0.5 TU, depending on measurement duration (Barešić et al., 2010, 2011, 2013; Vreča et al., 2014).

Tritium activity concentration in monthly samples collected between July 2012 and December 2024 was determined at O-2 JSI. Water samples were first distilled with addition of activated charcoal to adsorb possible other volatile radionuclides and after addition of the Na_2O_2 to the 250 mL of distilled water samples, they were electrolyzed until volume of less than 20 mL. Then second distil-

lation was performed and distilled samples were measured on liquid scintillation counter Quantulus 1220 (Perkin Elmer). Typical detection limits were about 0.15 Bqkg⁻¹. The method prior to instrumental analysis was the same also for TriCarb 3170 TR/SL; typical detection limits were about 0.21 Bqkg⁻¹. Results were reported in Bqkg⁻¹ but for the purpose of this paper, results are expressed in Tritium Units (1 TU = 0.118 BqL⁻¹). Given the low mineralization of precipitation, the density of water samples was assumed to be 1 kg L⁻¹, an approximation commonly applied in precipitation isotope studies.

Meteorological data

Meteorological data were obtained from a synoptic station Ljubljana (Bežigrad) (amount of precipitation (P) and air temperature (T), WGS84: 46.065507° N, 14.512352° E; 299 m a.s.l.) and from an automatic station Ljubljana (Hrastje) (T, 46.0743126° N, 14.553962° E; 290 m a.s.l.). Both stations are a part of the National meteorological network and the data was acquired from meteorological archive of the Slovenian Environment Agency for Ljubljana (Bežigrad) (Slovenian Environmental Agency (ARSO), 2025) and for Ljubljana (Hrastje) (ARSO, M. Demšar, personal communication) while for Ljubljana (Reaktor), P was recorded by JSI.

Data reduction

After collecting all results, we had to decide which data would be included in SLONIP database and used for future evaluation (Vreča, Štrok, et al., 2017). For tritium data, no selection was needed because each sample was measured only in one laboratory and the same measurement technique was used. Contrary, the stable isotopic composition was determined in 3 laboratories with different techniques. Decision for final data used for the SLONIP database (<https://slonip.ijs.si/>) was made using the modified approach applied for evaluation of stable isotope results in proficiency tests (PT) organized by IAEA (i.e. WICO 2016; Vreča & Žigon, 2016). The whole stable isotope dataset for Ljubljana since 1981 with data attributes is available in Gačnik et al. (2026; Supplementary material at <https://doi.org/10.1016/j.envres.2025.123286>; file: 1-s2.0-S0013935125025393-mm2.xlsx).

The isotopic composition of precipitation dataset for period 2011–2024 together with the tritium activity concentration and precipitation data for Reaktor is presented in this paper.

The approach of data reduction described by Vreča et al. (2008, 2014) for Ljubljana isotope re-

cords 1981–2006 and 2007–2010 was used. The minimum required number of data fulfilled the requirement of eight monthly measured samples per year and more than 70 % of total P collected per year (IAEA, 1992). Basic descriptive statistics, i.e. mean, minimum and maximum values were determined. Deuterium excess was calculated as $d\text{-excess} = \delta^2\text{H} - 8 \times \delta^{18}\text{O}$ (Dansgaard, 1964) and reported in ‰ to 1 decimal.

Furthermore, mean values weighted by P recorded during sampling period at the Ljubljana (Reaktor) and Ljubljana (Bežigrad) were calculated from all monthly data, and then summed over all collected samples per year and per month. Summation was also performed over each season: winter (December, January, February), spring (March, April, May), summer (June, July, August) and autumn (September, October, November). Oxygen-temperature correlation was calculated using T data provided by ARSO from Ljubljana (Bežigrad) and Ljubljana (Hrastje) which is close to Ljubljana (Reaktor).

Descriptive statistics (mean, median, quartiles, and range) and data visualization was done in R version 4.4.2 (R Core Team, 2021) using R packages “tidyverse” (Wickham et al., 2019), “readxl” (Wickham & Bryan, 2025), and “ggcorrplot” (Kassambara, 2023). For the geospatial plot (Slovenia map), packages “rnatualearth” (Massicotte & South, 2025) and “sf” (Pebesma, 2018) were used. Assessment of statistical differences between precipitation-weighted means of isotopic variables obtained using P values for Ljubljana (Bežigrad) and Ljubljana (Reaktor) was done using Diebold-Mariano test and package “forecast” (Hyndman & Khandakar, 2008). In the test, the forecast horizon was set to 1 because corresponding annual values (without a time shift) were compared, and a squared-error loss function (power = 2) was used to give greater weight to larger differences between the two isotope reconstructions. Unlike a paired t-test, this method accounts for temporal autocorrelation in the isotope records and therefore provides a robust assessment of whether the choice of precipitation station systematically influences the annual isotopic signals (Hyndman & Khandakar, 2008). The local meteoric water lines (LMWLs, $\delta^2\text{H}$ versus $\delta^{18}\text{O}$ linear regressions) were calculated using precipitation-weighted reduced major axis regression (PWRMA) following the suggestions in references (Crawford et al., 2014; Hughes & Crawford, 2012). The formulation of the regressions is described in more detail in the framework of the SLONIP platform (Vreča et al., 2022). Statistical significance of differences

between LMWLs computed with P data obtained from Ljubljana (Bežigrad) and Ljubljana (Reaktor) was tested using the analysis of covariance (ANCOVA). For T correlations with $\delta^2\text{H}$ and $\delta^{18}\text{O}$, ordinary least squares regression (OLS) was applied together with Pearson correlation tests (using pairwise complete observations).

Results and discussion

Meteorological data

For Ljubljana (Bežigrad), the maximum P value of 469 mm was recorded in September 2022, while the minimum of 0.1 mm was recorded in December 2016 (Fig. 2a). The largest mean monthly P values were observed in September (186 mm), while the lowest were observed in March (78 mm) (Fig. 2b). The year 2014 recorded the largest total P (1851 mm), while 2011 recorded the lowest total (998 mm). On average, a total yearly P of 1411 mm was observed for the 2011–2024 period, which is lower than the 2007–2010 mean yearly total (1472 mm) (Table 2). In comparison to Ljubljana (Reaktor), the mean monthly P was always higher at Ljubljana (Bežigrad) (Fig. 2b). On average, a total yearly P of 1271 mm was observed for the 2011–2024 period at Ljubljana (Reaktor), which is 140 mm lower than the mean value at Ljubljana

(Bežigrad). The relationship between P at Ljubljana (Reaktor, P_{Reaktor}) and Ljubljana (Bežigrad, $P_{\text{Bežigrad}}$) can be described by the following linear relationship (Pearson, $r = 0.96$):

$$P_{\text{Reaktor}} = 0.9 \times P_{\text{Bežigrad}} + 2.8 \quad (2)$$

During extreme nationwide flood events in Slovenia in August 2023, the monthly P (299 mm) was not as high in Ljubljana as in September 2022 (469 mm) (Fig. 2a). Nonetheless, the year 2023 recorded the second-highest total P (1814 mm) (Table 2). Additionally, the two-month and three-month cumulative P values (sum of prior P) were the largest in August 2023 (559 mm and 701 mm, respectively), indicating an extended rainy period prior to the flooding event.

The maximum mean T of 24.5 °C was recorded for July 2022, while the minimum mean T of −3.2 °C was recorded for Ljubljana (Bežigrad) in January 2017 (Fig. 2a). The 2011–2024 period mean T of 12.2 °C was higher than the 2007–2010 period mean T of 11.5 °C (Table 2). When looking at monthly means, July was the warmest month with 22.9 °C while January was the coldest month with 1.9 °C (Fig. 2b). Yearly means show that 2024 was the warmest year with 13 °C, while 2013 was the coldest with 11.6 °C (Table 2). At Ljubljana

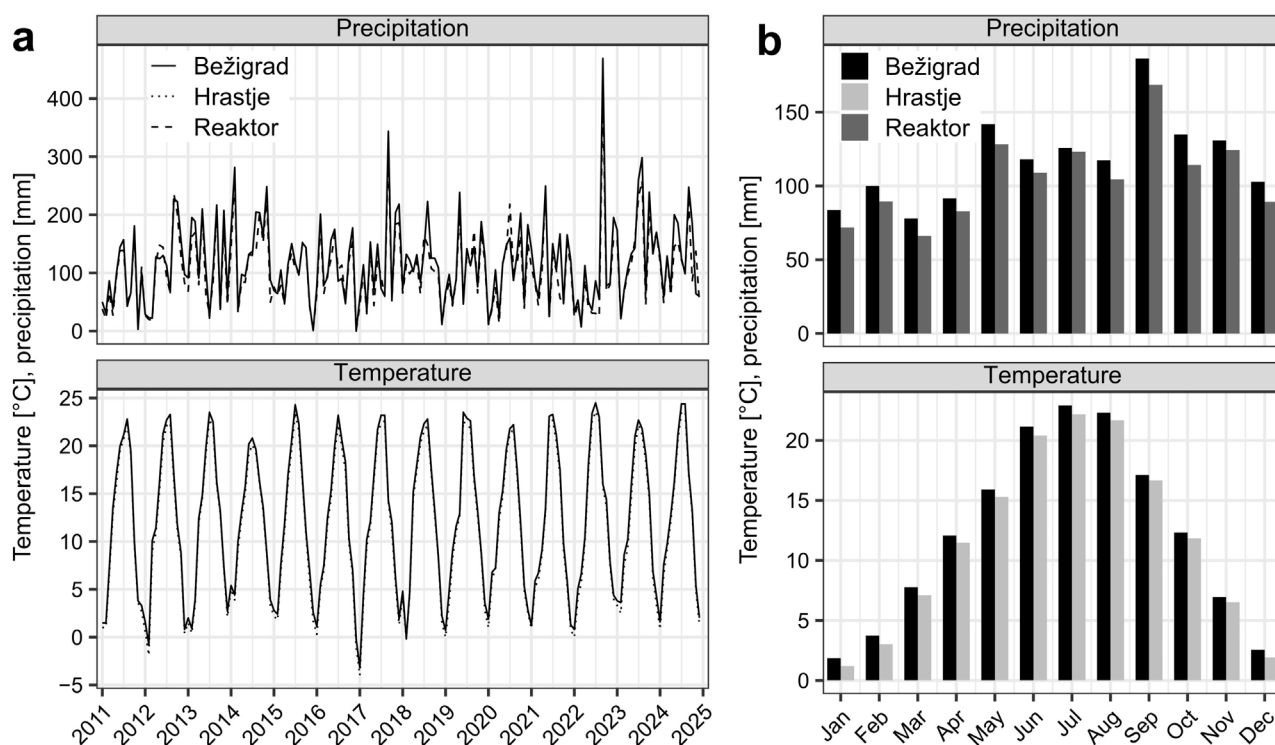


Fig. 2. Precipitation amount (Ljubljana (Bežigrad) and Ljubljana (Reaktor)) and temperature (Ljubljana (Bežigrad) and Ljubljana (Hrastje)) during the period 2011–2024 representing a) raw data in monthly resolution and b) means per month.

Table 2. Annual mean precipitation (P) and temperature (T) for Ljubljana (Bežigrad – “Be”, Reaktor – “Re”, and Hrastje – “Hr”) from 2011 to 2024, with a comparison of the 2011–2024 means to those from 2007–2010.

Year	P (total), Be [mm]	P (total), Re [mm]	P difference Be – Re	T (mean), Be [°C]	T (mean), Hr [°C]	T difference Be – Re
2011	998	919	80	11.8	11.3	0.5
2012	1339	1283	57	12.0	11.3	0.7
2013	1531	1330	201	11.6	11.1	0.5
2014	1851	1649	202	12.6	12.1	0.5
2015	1106	1047	59	12.2	11.5	0.7
2016	1317	1250	67	11.8	11.0	0.8
2017	1531	1370	161	11.9	11.3	0.6
2018	1377	1198	178	12.5	12.0	0.5
2019	1379	1309	70	12.5	11.9	0.6
2020	1262	1186	77	12.1	11.6	0.5
2021	1442	1205	237	11.5	11.0	0.5
2022	1257	1014	243	12.9	12.2	0.7
2023	1814	1661	153	12.7	11.9	0.8
2024	1553	1373	180	13.0	12.4	0.6
2011-2024 mean	1411	1271	140	12.2	11.6	0.6
2007-2010 mean (Vreča et al., 2014)	1472	1338	134	11.5	10.9	0.6

(Hrastje), the T values were systematically lower than at Ljubljana (Bežigrad) (Fig. 2b, lower part), with a mean difference of 0.6 °C for the yearly average T. Values for T at the two stations correlated strongly ($r > 0.99$). The maxima of 23.6 °C and minima of –4.0 °C were recorded at Ljubljana (Hrastje) for July 2022 and January 2017, on the same months as the Ljubljana (Bežigrad) extremes.

Isotopic composition data ($\delta^2\text{H}$, $\delta^{18}\text{O}$ and d-excess)

The highest $\delta^{18}\text{O}$ value of –1.65 ‰ was recorded in March 2012, while the lowest $\delta^{18}\text{O}$ value (–16.43 ‰) was recorded in February 2012 (Fig. 3, Table 3). The maximum and minimum $\delta^2\text{H}$ values were observed during the same months as $\delta^{18}\text{O}$, reaching –7.3 ‰ and –121.4 ‰, respectively. For d-excess, the maximum value of 18.0 ‰ was recorded in February 2023 while the minimum value of 2.7 ‰ was recorded in two months, June 2021 and August 2022 (Fig. 3). The variability of $\delta^{18}\text{O}$ and $\delta^2\text{H}$ follows the annual T cycle, with the highest values observed during summer months, and lowest during winter months. For d-excess, the variability is more complex; however, autumn months (September, October, and November) generally exhibit the highest d-excess values throughout the year. Compared to 2007–2010, 2011–2024

shows higher values for all stable isotopic variables: –60.0 ‰ vs –56.1 ‰ for $\delta^2\text{H}$, –8.78 ‰ vs –8.41 ‰ for $\delta^{18}\text{O}$, and 10.3 ‰ vs 11.1 ‰ for d-excess, respectively (Table 4). The temporal changes were confirmed also with detailed trend analysis of the whole stable isotope record (Gačnik et al., 2026).

Table 3. Complete time series of the isotopic composition of precipitation at Ljubljana (Reaktor) for period 2011–2024. Notations: “*” – see Gačnik et al. (2026) for details, “A” – not determined, “B” – not enough sample for analysis, and “C” – tube blocked.

Month/ Year	$\delta^2\text{H}^*$ ‰	$\delta^{18}\text{O}^*$ ‰	d* ‰	A(^3H) TU	P _{Re} mm
01/11	–68.9	–9.95	10.7	5.3	37.8
02/11	–76.3	–11.00	11.7	8.3	20.7
03/11	–32.5	–5.70	13.1	7.0	66.9
04/11	–46.2	–6.67	7.2	12.6	27.4
05/11	–55.9	–8.24	10.0	12.7	93.0
06/11	–37.7	–5.72	8.1	8.6	138.3
07/11	A	–8.22	A	10.8	139.1
08/11	–36.3	–5.76	9.8	7.0	51.2
09/11	–29.2	–5.02	11.0	4.1	64.2
10/11	–66.1	–10.25	15.9	4.7	167.6
11/11	–36.5	–5.80	9.9	B	2.7

Month/ Year	$\delta^2\text{H}^*$ ‰	$\delta^{18}\text{O}^*$ ‰	d^* ‰	$A(^3\text{H})$ TU	P_{Re} mm
12/11	A	-10.57	A	6.4	109.7
01/12	-71.4	-10.31	11.1	4.8	26.9
02/12	-121.4	-16.43	10.0	8.9	19.9
03/12	-7.3	-1.65	5.9	7.3	19.2
04/12	-51.3	-7.58	9.3	8.6	118.4
05/12	-50.8	-7.06	5.7	11.9	147.7
06/12	-38.4	-5.96	9.3	10.0	144.2
07/12	-32.7	-5.16	8.6	11.3	92.0
08/12	-35.1	-5.45	8.5	7.2	65.7
09/12	-44.9	-7.03	11.3	5.1	236.7
10/12	-66.2	-9.86	12.7	4.6	201.4
11/12	-59.3	-8.95	12.3	5.4	127.8
12/12	-95.5	-13.59	13.2	4.6	82.6
01/13	-96.2	-13.34	10.5	3.8	68.6
02/13	-99.5	-13.58	9.1	3.1	162.4
03/13	-80.8	-11.29	9.5	6.9	169.6
04/13	-69.2	-9.62	7.8	8.2	79.6
05/13	-53.4	-8.02	10.8	9.9	204.9
06/13	-66.4	-9.10	6.4	13.1	61.4
07/13	-37.3	-5.38	5.7	11.4	30.4
08/13	-38.1	-5.92	9.3	10.8	84.6
09/13	-49.2	-7.70	12.4	5.5	210.6
10/13	-44.4	-6.88	10.6	5.4	33.8
11/13	-86.4	-12.64	14.7	3.7	179.8
12/13	-63.3	-9.13	9.7	3.3	44.3
01/14	-75.5	-10.54	8.8	4.0	143.1
02/14	-73.9	-10.69	11.6	4.9	261.6
03/14	-50.8	-7.67	10.6	4.0	30.8
04/14	-38.7	-5.84	8.0	11.1	85.4
05/14	-53.3	-7.73	8.5	8.0	83.6
06/14	-42.1	-6.44	9.4	5.6	132.0
07/14	-46.5	-6.86	8.4	11.2	137.0
08/14	-33.3	-5.63	11.7	7.4	136.3
09/14	-83.1	-11.76	11.0	11.5	203.9
10/14	-46.0	-7.35	12.8	5.1	151.7
11/14	-41.0	-7.09	15.7	4.4	233.8
12/14	-69.0	-10.17	12.4	6.5	49.7
01/15	-89.1	-12.63	11.9	2.4	75.6
02/15	-104.6	-14.78	13.6	6.5	62.9
03/15	-73.8	-10.48	10.0	5.7	78.4

Month/ Year	$\delta^2\text{H}^*$ ‰	$\delta^{18}\text{O}^*$ ‰	d^* ‰	$A(^3\text{H})$ TU	P_{Re} mm
04/15	-64.1	-8.91	7.2	7.4	47.0
05/15	-38.6	-6.08	10.0	7.0	108.1
06/15	-54.2	-8.11	10.7	6.6	135.0
07/15	-31.2	-5.18	10.2	7.2	105.9
08/15	C	C	C	C	99.0
09/15	-40.1	-6.90	15.1	5.0	152.2
10/15	-69.1	-10.16	12.2	4.3	139.9
11/15	-119.3	-16.10	9.5	4.6	41.8
12/15	-67.4	-9.74	10.5	B	1.2
01/16	-69.1	-9.81	9.4	4.3	64.4
02/16	-87.2	-12.01	8.9	3.8	188.7
03/16	-90.4	-12.70	11.2	5.1	64.7
04/16	-47.6	-7.56	12.9	6.3	98.2
05/16	-60.5	-8.46	7.2	12.0	123.8
06/16	-59.0	-8.23	6.8	10.2	166.1
07/16	-25.8	-4.33	8.8	8.4	105.9
08/16	-40.7	-6.28	9.5	8.2	113.4
09/16	-41.3	-6.23	8.5	5.1	49.0
10/16	-61.1	-9.37	13.9	5.8	122.8
11/16	-63.1	-9.75	14.9	4.2	153.4
12/16	B	B	B	B	A
01/17	-78.6	-11.18	10.8	2.5	44.0
02/17	-61.9	-9.11	11.0	5.5	102.2
03/17	-65.9	-9.51	10.2	6.0	29.8
04/17	-33.7	-5.57	10.9	7.8	143.2
05/17	-42.9	-6.04	5.4	9.0	44.0
06/17	-24.6	-4.47	11.2	5.6	122.1
07/17	-20.0	-3.75	10.0	7.3	94.2
08/17	-34.1	-5.46	9.6	6.4	59.9
09/17	-48.6	-7.84	14.1	4.3	308.6
10/17	-48.4	-7.64	12.7	3.8	52.0
11/17	-81.9	-12.00	14.1	3.6	183.8
12/17	-86.4	-12.50	13.6	4.0	186.5
01/18	-47.0	-7.27	11.2	3.1	65.4
02/18	-107.2	-14.79	11.1	4.9	114.4
03/18	-71.3	-9.96	8.4	4.5	98.2
04/18	-38.6	-6.17	10.8	8.0	109.4
05/18	-33.6	-5.40	9.6	11.3	119.4
06/18	-39.8	-5.56	4.7	14.6	63.4
07/18	-34.9	-5.80	11.5	13.0	163.1

Month/ Year	$\delta^2\text{H}^*$ ‰	$\delta^{18}\text{O}^*$ ‰	d^* ‰	$A(^3\text{H})$ TU	P_{Re} mm
08/18	-41.4	-6.50	10.6	14.3	149.0
09/18	-33.7	-5.93	13.7	5.6	107.9
10/18	-31.0	-5.36	11.9	4.8	102.5
11/18	-68.2	-10.31	14.3	5.1	94.5
12/18	-74.3	-10.57	10.3	B	11.2
01/19	-74.8	-10.98	13.0	3.9	59.7
02/19	-67.1	-9.41	8.2	3.3	82.8
03/19	-41.4	-6.69	12.2	8.5	43.3
04/19	-51.1	-7.68	10.3	8.6	87.0
05/19	-75.3	-10.28	7.0	9.0	202.2
06/19	-27.9	-5.18	13.6	9.7	62.7
07/19	-30.8	-4.74	7.2	11.4	129.3
08/19	-37.5	-5.85	9.3	8.8	113.9
09/19	-37.0	-6.49	15.0	9.0	172.8
10/19	-39.9	-6.63	13.2	4.6	65.7
11/19	-54.6	-8.69	14.9	3.9	169.8
12/19	-96.9	-13.32	9.6	3.2	120.1
01/20	-37.2	-6.12	11.8	B	11.2
02/20	-42.5	-6.72	11.2	4.4	38.3
03/20	-49.9	-7.42	9.4	5.7	74.1
04/20	-49.0	-6.97	6.8	B	12.9
05/20	-32.3	-5.20	9.3	7.1	117.1
06/20	-44.0	-6.67	9.4	9.6	139.8
07/20	-37.6	-5.78	8.7	9.8	218.1
08/20	-24.3	-4.09	8.4	9.2	102.7
09/20	-65.5	-9.76	12.6	5.6	115.4
10/20	-67.4	-10.10	13.4	4.7	165.1
11/20	-99.2	-13.44	8.3	4.4	39.3
12/20	-70.3	-10.78	16.0	5.2	151.7
01/21	-80.2	-11.96	15.5	5.0	109.4
02/21	-69.3	-10.12	11.7	5.1	81.6
03/21	-48.2	-7.84	14.5	4.8	43.8
04/21	-54.3	-8.42	13.1	7.6	103.9
05/21	-45.3	-6.99	10.6	6.5	249.7
06/21	-28.4	-3.89	2.7	12.9	20.4
07/21	-45.7	-6.80	8.7	10.4	127.6
08/21	-42.3	-6.65	10.9	8.4	104.2
09/21	-53.0	-7.90	10.2	7.4	56.9
10/21	-47.0	-7.59	13.7	4.9	45.3
11/21	-73.7	-11.20	15.9	4.1	149.7

Month/ Year	$\delta^2\text{H}^*$ ‰	$\delta^{18}\text{O}^*$ ‰	d^* ‰	$A(^3\text{H})$ TU	P_{Re} mm
12/21	-92.4	-13.11	12.4	2.5	112.7
01/22	-68.2	-10.01	11.9	5.1	23.6
02/22	-36.0	-6.02	12.2	4.6	46.8
03/22	-54.8	-7.88	8.2	B	8.7
04/22	-69.1	-10.05	11.3	9.2	88.5
05/22	-43.2	-6.26	6.9	14.0	39.0
06/22	-27.8	-4.11	5.1	9.3	30.8
07/22	-17.5	-2.73	4.3	12.7	30.3
08/22	-27.6	-3.79	2.7	11.4	24.4
09/22	-46.6	-7.44	12.9	4.7	413.6
10/22	-30.4	-5.52	13.8	3.6	67.6
11/22	-66.9	-9.76	11.2	2.6	79.6
12/22	-80.9	-11.85	13.9	2.7	161.1
01/23	-94.5	-13.39	12.6	3.1	156.7
02/23	-47.4	-8.17	18.0	6.6	20.1
03/23	-49.6	-7.67	11.8	4.7	67.6
04/23	-51.3	-7.62	9.7	4.4	98.5
05/23	-65.4	-9.17	8.0	11.0	116.6
06/23	-43.4	-6.57	9.2	14.1	156.7
07/23	-29.2	-4.92	10.2	7.2	230.0
08/23	-37.5	-6.34	13.2	6.5	258.6
09/23	-37.9	-5.83	8.7	3.9	44.5
10/23	-50.3	-7.75	11.7	2.1	196.0
11/23	-56.9	-9.02	15.3	2.8	146.5
12/23	-83.3	-11.92	12.1	3.1	169.1
01/24	-88.7	-12.22	9.1	3.8	119.6
02/24	-72.3	-9.92	7.1	5.2	49.0
03/24	-58.6	-8.64	10.5	6.4	129.3
04/24	-68.4	-10.11	12.5	7.8	60.9
05/24	-45.1	-6.88	9.9	8.8	145.2
06/24	-38.0	-6.03	10.2	9.2	153.7
07/24	-30.9	-5.10	9.9	9.4	122.4
08/24	-30.7	-4.65	6.5	8.4	98.5
09/24	-62.9	-9.43	12.5	4.7	221.8
10/24	-82.1	-11.71	11.6	3.2	86.5
11/24	-46.6	-7.72	15.2	4.3	137.3
12/24	-68.6	-10.61	16.3	3.0	48.7

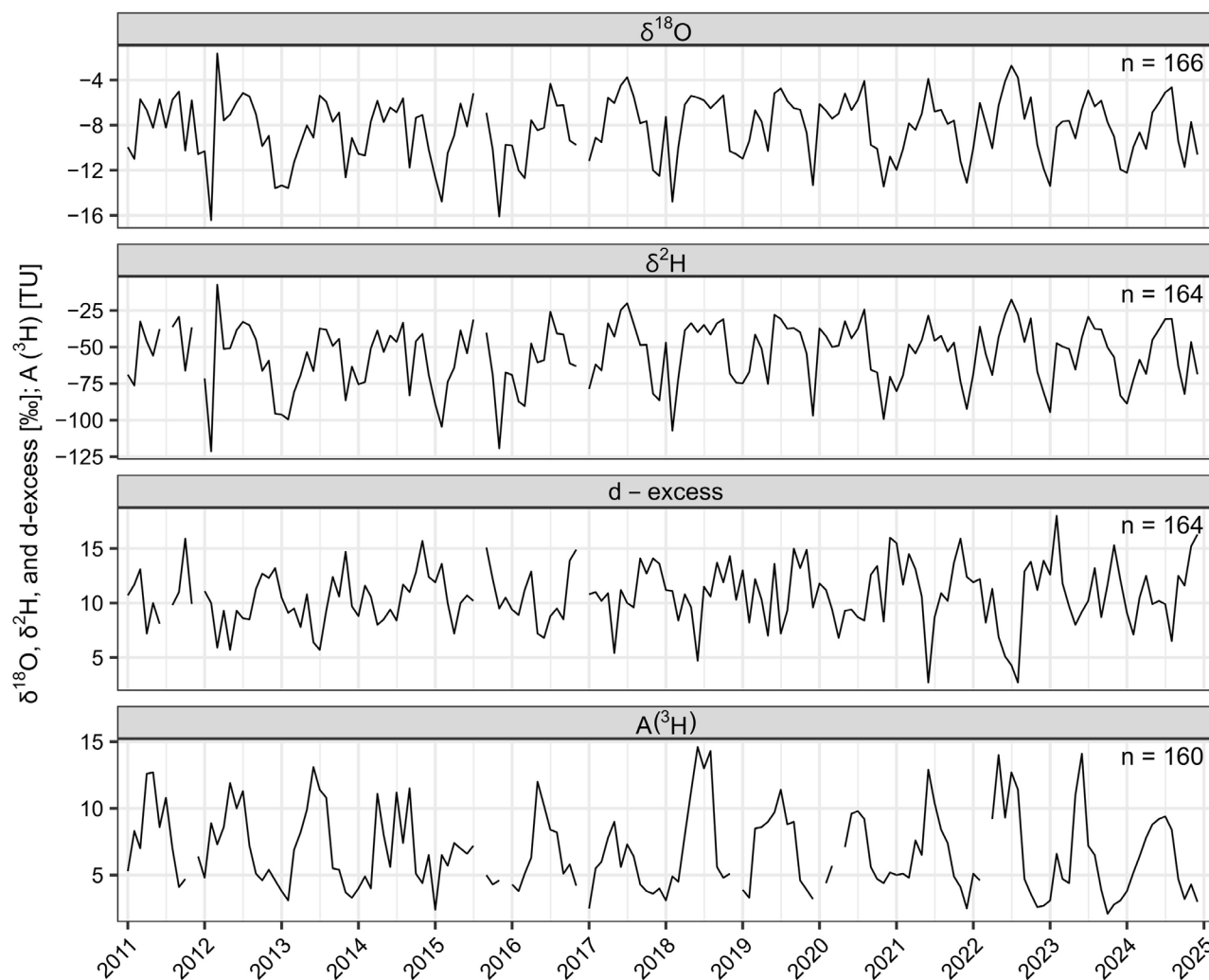


Fig. 3. Individual monthly values for $\delta^{18}\text{O}$, $\delta^2\text{H}$, and d-excess in precipitation at Ljubljana (Reaktor), 2011–2024. The number of measurements available for each respective time series is denoted with n .

Table 4. Annual precipitation-weighted means of $\delta^{18}\text{O}$, $\delta^2\text{H}$, d-excess, and $A(^3\text{H})$. Summary statistics of the yearly values and comparison with previous period are shown at the bottom of the table.

Year	Bežigrad precipitation-weighted				Reaktor precipitation-weighted			
	$\delta^{18}\text{O}$	$\delta^2\text{H}$	d-excess	$A(^3\text{H})$	$\delta^{18}\text{O}$	$\delta^2\text{H}$	d-excess	$A(^3\text{H})$
2011	-7.65	-49.7	11.5	7.9	-7.58	-49.2	11.5	7.8
2012	-8.06	-54.1	10.4	7.2	-7.94	-53.3	10.2	7.3
2013	-10.03	-69.8	10.5	6.7	-9.92	-68.8	10.6	6.6
2014	-8.39	-55.8	11.2	6.8	-8.44	-56.3	11.2	6.9
2015	-9.02	-60.8	11.4	5.7	-9.05	-60.9	11.5	5.7
2016	-9.01	-61.9	10.2	6.8	-8.80	-60.2	10.2	6.8
2017	-8.38	-54.9	12.2	5.1	-8.28	-54.1	12.2	5.1
2018	-7.57	-49.7	10.8	8.6	-7.52	-49.3	10.9	8.6
2019	-8.33	-55.9	10.7	7.1	-8.18	-54.5	10.9	7.2
2020	-8.04	-53.2	11.2	6.7	-7.71	-50.8	10.9	7.1
2021	-8.85	-58.8	12.0	6.4	-8.87	-58.8	12.1	6.3
2022	-7.78	-51.0	11.3	5.9	-8.05	-52.6	11.8	5.4
2023	-8.07	-53.1	11.5	5.7	-8.14	-53.6	11.6	5.9
2024	-8.50	-57.2	10.8	6.3	-8.28	-55.3	11.0	6.4
Minimum	-10.03	-69.8	10.2	5.1	-9.92	-68.8	10.2	5.2
Maximum	-7.57	-49.7	12.2	8.6	-7.52	-49.2	12.2	8.6
2011–2024 mean	-8.41	-56.1	11.1	6.7	-8.34	-55.6	11.2	6.7
2007–2010 mean (Vreča et al., 2014)	-8.78	-60.0	10.3	8.3	-8.71	-59.4	10.3	8.5

Previous studies of precipitation stable isotopes in Ljubljana (Vreča et al., 2008, 2014) have investigated the differences in precipitation-weighting of isotopic means when weighting with two different P datasets – Ljubljana (Reaktor) and Ljubljana (Bežigrad). Comparison of annual precipitation-weighted means obtained using Bežigrad and Reaktor P values (Table 4) reveals that there are no significant differences between the obtained precipitation-weighted annual timeseries for all

isotopic variables (Diebold-Mariano, $p > 0.05$). To be consistent with previous reports on the isotopic composition of precipitation in Ljubljana (Vreča et al., 2008, 2014), all further precipitation-weighted means were obtained using the Ljubljana (Bežigrad) P values. Although no statistically significant differences were observed between isotope series weighted using Bežigrad and Reaktor precipitation data, the spatial separation between the two stations is very small and their climatological

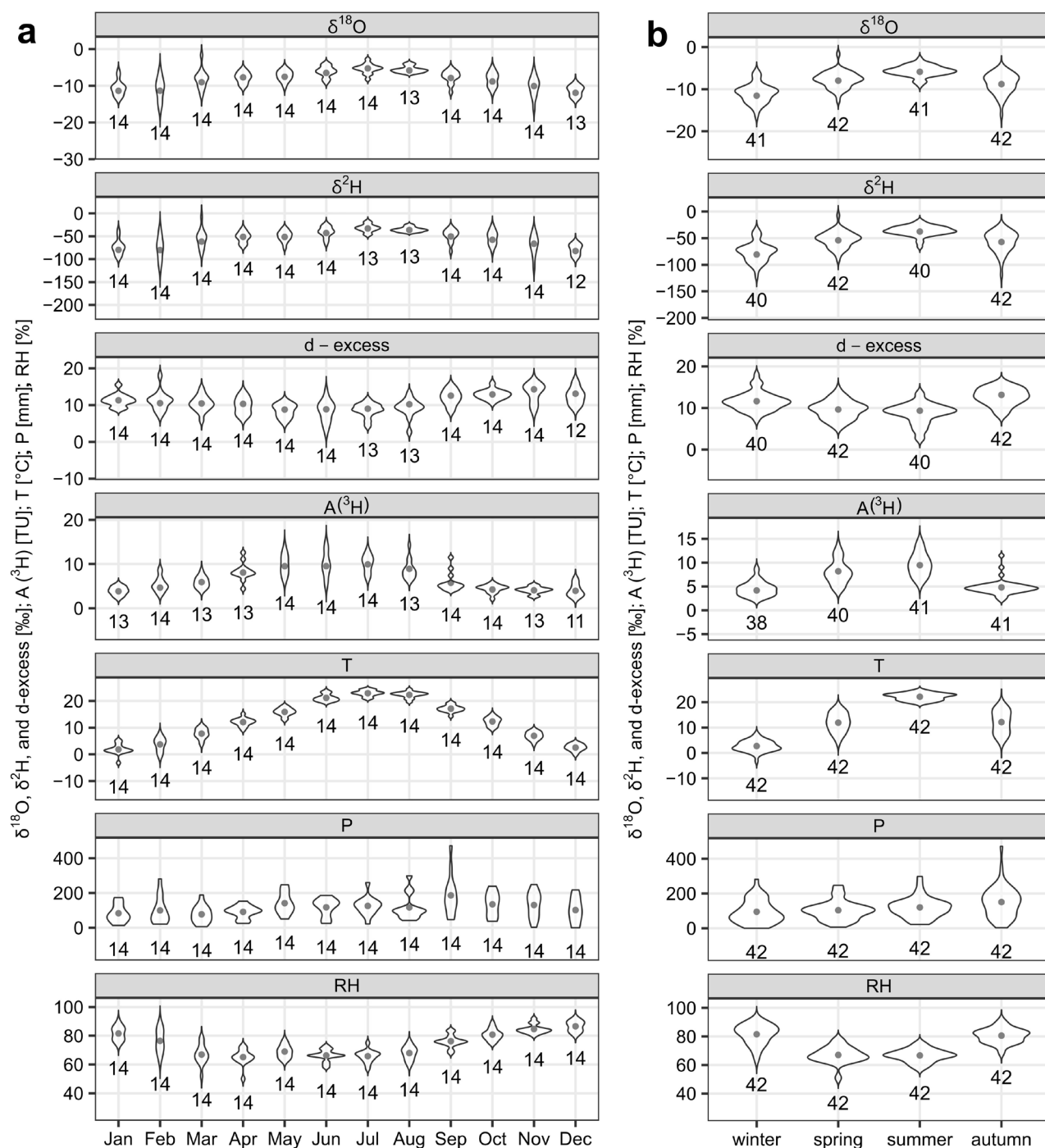


Fig. 4. Precipitation-weighted (Ljubljana (Bežigrad) precipitation amount) means of $\delta^{18}\text{O}$, $\delta^2\text{H}$, d-excess, $A(^3\text{H})$, with additional data on P, T, and relative humidity (RH) for the period 2011–2024, a) grouped by month and b) grouped by season. The numbers below violin plots represent the number of measurements available for each respective point/violin plot. For all variables besides P, the violin plots extend beyond the actual data range due to extrapolation via kernel density estimation. The extrapolation was not used for P due to physically-meaningless negative P values.

regimes are nearly identical; therefore, collocated measurements of P and isotopic composition remain the recommended best practice.

When looking at the precipitation-weighted monthly mean isotopic composition (Fig. 3a, Table 5), the lowest $\delta^2\text{H}$ and $\delta^{18}\text{O}$ values occur during the winter months, while the highest values occur during the summer months. The values during winter months range from -80.2‰ to -76.4‰ for $\delta^2\text{H}$ and from -11.8‰ to -11.3‰ for $\delta^{18}\text{O}$. Summer monthly means range from -43.1‰ to -30.1‰ for $\delta^2\text{H}$ and from -6.5‰ to -5.5‰ for $\delta^{18}\text{O}$. These values further confirm the dependence of hydrogen and oxygen isotopes in precipitation on the annual T cycle as confirmed also by detailed trend analysis of the whole stable isotope record (Gačnik et al., 2026). The distribution (spread) of $\delta^2\text{H}$ and $\delta^{18}\text{O}$ is much wider during September–March than during April–August (violin plots, Fig. 4a), and visually resembles the influence of different monthly T and relative humidity variations but also shifts in moisture sources, increased atmospheric instability or mixing of Atlantic, Mediterranean or continental air masses with the intrusion of Arctic air masses during the colder period of the year. More detailed discussion requires additional climatological analysis and is beyond the scope of this paper.

For d-excess, the highest precipitation-weighted mean values (Fig. 4a, Table 5) during autumn months range from 12.5‰ to 14.5‰ . Notably, November is the only month with $> 14\text{‰}$ mean monthly d-excess, while d-excess of other months falls below 13‰ . This indicates that November is the most unique month with regards to d-excess in Ljubljana. The spread of d-excess values is com-

parable between different months, although June shows the widest distribution of d-excess values (violin plots, Fig. 4a). Low d-excess values under 5‰ all correspond to summer months, and not to months with low precipitation and coldest months, as was observed for 2007–2010 by Vreča et al. (2014). This indicates either the influence of secondary processes such as evaporation that alters the d-excess as the air masses moves inland (Gat et al., 1994) or d-excess values change as precipitation falls through the warm and dry atmosphere (Araguás-Araguás et al., 2000; Gat, 1996; Peng et al., 2004) or as the precipitation sample sits in the precipitation collector (Harvey, 2005). On the other hand, d-excess values greater than 15‰ are primarily associated with autumn months, with a slight occurrence in the winter months, which is in agreement with previous investigations of the Ljubljana dataset (Gačnik et al., 2026; Vreča et al., 2008, 2014).

Seasonal precipitation-weighted means of isotopic data (Fig. 4b, Table 5) show similar findings as monthly means, $\delta^2\text{H}$ and $\delta^{18}\text{O}$ following the yearly T cycle with winter minima and summer maxima. The spread of $\delta^2\text{H}$ and $\delta^{18}\text{O}$ values is the smallest during summer (violin plots, Fig. 4b), caused by T and relative humidity variations as well as mixing of different air masses during different seasons. For d-excess, autumn is the season with clearly the highest mean d-excess values. This can be attributed to the Mediterranean-derived precipitation (Gačnik et al., 2026), which carries characteristically high d-excess values (Rozanski et al., 1993). Autumn is typically influenced by the Mediterranean precipitation in this geographical region (Vreča et al., 2008).

Table 5. Monthly and seasonal precipitation-weighted means of $\delta^{18}\text{O}$, $\delta^2\text{H}$, d-excess, and $\text{A}(\text{^3H})$ (Ljubljana (Bežigrad) precipitation amount) for the period 2011–2024.

Month	$\delta^2\text{H}$	$\delta^{18}\text{O}$	d-excess	^3H	Season	$\delta^2\text{H}$	$\delta^{18}\text{O}$	d-excess	$\text{A}(\text{^3H})$
January	−79.6	−11.4	11.3	3.8	Winter	−78.7	−11.5	11.3	4.1
February	−80.2	−11.3	10.5	4.7	Spring	−52.5	−8.0	9.6	8.1
March	−61.7	−9.0	10.4	5.9	Summer	−36.3	−5.8	8.9	9.3
April	−51.3	−7.7	10.3	7.9	Autumn	−56.6	−8.8	13.2	4.8
May	−51.5	−7.5	8.8	9.5					
June	−43.1	−6.5	8.9	9.5					
July	−30.1	−5.5	8.2	9.9					
August	−34.1	−5.5	9.6	8.4					
September	−50.4	−7.9	12.6	5.8					
October	−57.7	−8.8	12.9	4.2					
November	−66.3	−10.1	14.3	4.1					
December	−76.4	−11.8	12.2	3.9					

Local meteoric water lines

In comparison to 2007–2010, both slope and intercept of the precipitation-weighted reduced major axis regression (PWRMA) for 2011–2024 are lower (Table 6). This may indicate that the isotopic composition of precipitation in Ljubljana is getting progressively heavier, which could be either due to evaporative effects of rising T or due to changes in source origin of water vapour (for details see

Gačnik et al., 2026). The difference between precipitation-weighted LMWLs for Reaktor and Bežigrad during the period 2011–2024 is minimal, and any discrepancy falls within the uncertainty of the regression coefficients. Furthermore, analysis of covariance (ANCOVA) showed no statistically significant difference between the LMWLs for each year ($p > 0.05$).

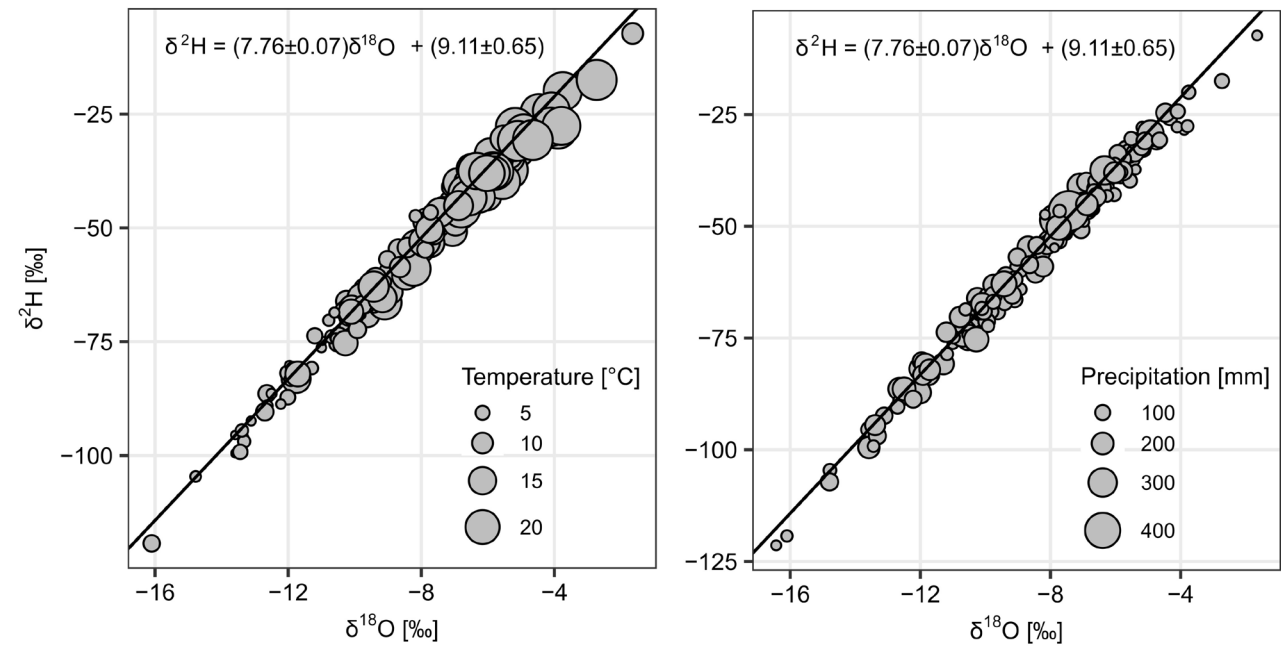


Fig. 5. $\delta^2\text{H}$ versus $\delta^{18}\text{O}$ plots for the whole 2011–2024 period, where size of the point corresponds to either temperature or precipitation amount.

Table 6. Comparison of yearly precipitation-weighted reduced major axis (PWRMA) regressions, weighted using precipitation amounts obtained at the Ljubljana (Bežigrad) and Ljubljana (Reaktor) stations; 2011–2024.

Year	PWRMA, Bežigrad precipitation	PWRMA, Reaktor precipitation
2011	$\delta^2\text{H} = (7.19 \pm 0.38) \delta^{18}\text{O} + (5.29 \pm 3)$	$\delta^2\text{H} = (7.13 \pm 0.37) \delta^{18}\text{O} + (4.83 \pm 2.88)$
2012	$\delta^2\text{H} = (7.47 \pm 0.21) \delta^{18}\text{O} + (6.13 \pm 1.81)$	$\delta^2\text{H} = (7.46 \pm 0.23) \delta^{18}\text{O} + (5.97 \pm 1.93)$
2013	$\delta^2\text{H} = (7.89 \pm 0.27) \delta^{18}\text{O} + (9.35 \pm 2.83)$	$\delta^2\text{H} = (7.89 \pm 0.27) \delta^{18}\text{O} + (9.45 \pm 2.77)$
2014	$\delta^2\text{H} = (8.15 \pm 0.34) \delta^{18}\text{O} + (12.47 \pm 2.92)$	$\delta^2\text{H} = (8.13 \pm 0.34) \delta^{18}\text{O} + (12.35 \pm 3)$
2015	$\delta^2\text{H} = (8.01 \pm 0.21) \delta^{18}\text{O} + (11.49 \pm 2.04)$	$\delta^2\text{H} = (8.01 \pm 0.22) \delta^{18}\text{O} + (11.58 \pm 2.08)$
2016	$\delta^2\text{H} = (7.86 \pm 0.42) \delta^{18}\text{O} + (8.97 \pm 3.88)$	$\delta^2\text{H} = (7.86 \pm 0.4) \delta^{18}\text{O} + (8.95 \pm 3.59)$
2017	$\delta^2\text{H} = (7.61 \pm 0.2) \delta^{18}\text{O} + (8.89 \pm 1.74)$	$\delta^2\text{H} = (7.62 \pm 0.18) \delta^{18}\text{O} + (9.02 \pm 1.57)$
2018	$\delta^2\text{H} = (7.95 \pm 0.24) \delta^{18}\text{O} + (10.46 \pm 1.95)$	$\delta^2\text{H} = (7.96 \pm 0.23) \delta^{18}\text{O} + (10.59 \pm 1.87)$
2019	$\delta^2\text{H} = (8.29 \pm 0.39) \delta^{18}\text{O} + (13.12 \pm 3.37)$	$\delta^2\text{H} = (8.32 \pm 0.39) \delta^{18}\text{O} + (13.49 \pm 3.32)$
2020	$\delta^2\text{H} = (7.26 \pm 0.24) \delta^{18}\text{O} + (5.2 \pm 2.05)$	$\delta^2\text{H} = (7.24 \pm 0.23) \delta^{18}\text{O} + (5.05 \pm 1.82)$
2021	$\delta^2\text{H} = (7.21 \pm 0.24) \delta^{18}\text{O} + (5.03 \pm 2.24)$	$\delta^2\text{H} = (7.25 \pm 0.24) \delta^{18}\text{O} + (5.42 \pm 2.2)$
2022	$\delta^2\text{H} = (7.2 \pm 0.28) \delta^{18}\text{O} + (5.09 \pm 2.34)$	$\delta^2\text{H} = (7.4 \pm 0.28) \delta^{18}\text{O} + (6.94 \pm 2.36)$
2023	$\delta^2\text{H} = (7.82 \pm 0.25) \delta^{18}\text{O} + (10.06 \pm 2.08)$	$\delta^2\text{H} = (7.81 \pm 0.25) \delta^{18}\text{O} + (10.02 \pm 2.13)$
2024	$\delta^2\text{H} = (7.72 \pm 0.27) \delta^{18}\text{O} + (8.45 \pm 2.36)$	$\delta^2\text{H} = (7.76 \pm 0.31) \delta^{18}\text{O} + (8.98 \pm 2.69)$
2011–2024	$\delta^2\text{H} = (7.76 \pm 0.07) \delta^{18}\text{O} + (9.11 \pm 0.65)$	$\delta^2\text{H} = (7.78 \pm 0.07) \delta^{18}\text{O} + (9.29 \pm 0.65)$
2007–2010 (Vreča et al., 2014)	$\delta^2\text{H} = (7.93 \pm 0.21) \delta^{18}\text{O} + (9.68 \pm 1.93)$	$\delta^2\text{H} = (7.94 \pm 0.21) \delta^{18}\text{O} + (9.76 \pm 1.91)$

The $\delta - \delta$ plots (Fig. 5) indicate that in general, high $\delta^2\text{H}$ and $\delta^{18}\text{O}$ values are associated with high T values and vice-versa ($\delta^2\text{H}$ and $\delta^{18}\text{O}$ are highly correlated with T), but there is no significant correlation with P (Fig. 6). The extreme isotopic composition values (low and high) occur when P values are low (Fig. 5).

Tritium activity

The lowest value for tritium activity of 2.1 TU was recorded on October 2023 while the highest value of 14.6 TU was recorded on March 2018 (Fig. 2, Table 3). July is the month with the highest means (9.9 TU), while January is the month with the lowest means (3.8 TU) (Table 5). Seasonal fluctuations show that highest values are observed in spring and summer, whereas lowest values are observed in autumn and winter (Table 5). The seasonality, characterized by summer maxima and winter minima, is typical of temperate regions in the Northern hemisphere. This pattern results from the spring rise of the troposphere, which leads to the injection of tritium-rich air from the stratosphere into the troposphere (Krajcar Bronić, Barešić, Sironić, et al., 2020; Rozanski et al., 1991). In addition, tritium production in the atmosphere is governed by the neutron flux, which reaches its maximum during the solar minimum sunspot numbers (Palcsu et al., 2018). This is also evidenced in annual precipitation-weighted mean tritium results (Table 4) where maximum value of 8.6 TU was found in 2018, which coincides with the onset of last solar sunspot minimum. The seasonal fluctuations in the period 2011–2024 dominate over the long-term decreasing trend, which was not the case for Ljubljana during 1981–2006 (Vreča et al., 2008). The long-term decrease in tritium activity is due to the radioactive decay of tritium released during nuclear testing (Rozanski et al., 1991). This long-term trend is now much less pronounced due to the exponential nature of radioactive decay, making seasonality the more prominent feature. The mean tritium activity of 6.7 TU for the period of 2011–2024 is lower than the mean of 8.3 TU for the period 2007–2010 (Vreča et al., 2014) (Table 4). Again, the decrease is caused by the radioactive decay of the global background tritium released during 1960s nuclear testing.

Temperature correlation

The ordinary least squares (OLS) regression for $\delta^2\text{H}$ and $\delta^{18}\text{O}$ at Ljubljana (Bežigrad) as a function of monthly T values at Ljubljana (Bežigrad) (T_{BE}) and Ljubljana (Hrastje) (T_{HR}) during 2011–2024 resulted in the following equations:

$$\delta^2\text{H} = 2.1 (\pm 0.2) * T_{BE} - 80 (\pm 2) \quad (3)$$

$$\delta^{18}\text{O} = 0.28 (\pm 0.02) * T_{BE} - 11.7 (\pm 0.3) \quad (4)$$

$$\delta^2\text{H} = 2.1 (\pm 0.2) * T_{HR} - 79 (\pm 2) \quad (5)$$

$$\delta^{18}\text{O} = 0.28 (\pm 0.02) * T_{HR} - 11.5 (\pm 0.3) \quad (6)$$

where the both $\delta^2\text{H}$ and $\delta^{18}\text{O}$ are strongly correlated with T_{BE} (Pearson, $r = 0.72$ and $r = 0.75$, respectively) and T_{HR} (Pearson, $r = 0.72$ and $r = 0.74$, respectively). The differences in regression coefficients, intercepts, and correlations between T_{BE} and T_{HR} are minimal. The regression equation for $\delta^{18}\text{O}$ as a function of T for the period 2007–2010 is similar to that for 2011–2024, with differences in the coefficients falling within the range of regression uncertainty. This correlation is typical of mid and high latitudes, where seasonally fluctuating T values cause variations in the P , due to the progressive degree of rainout from air masses as they cool off (Rozanski et al., 1993). Using a time series decomposition approach for the Ljubljana dataset (1981–2024), Gačnik et al. (2026) isolated the annual $\delta^2\text{H}$, $\delta^{18}\text{O}$, and T cycles from other oscillations with different frequencies and from noise. They observed coefficients of 2.57 ‰/°C for $\delta^2\text{H}$ and 0.32 ‰/°C for $\delta^{18}\text{O}$. These values are slightly higher than the values observed in the present study, most likely due to the improved ability of the time series decomposition approach to separate individual oscillatory components from overlapping cycles and noise. For groundwater in Ljubljana during the period 2009–2011, Mezga et al. (2014) observed a coefficient of 0.30 ‰/°C for $\delta^{18}\text{O}$, which is similar to the above discussed temperature-dependency coefficients of precipitation.

Besides the correlation with T , $\delta^2\text{H}$ and $\delta^{18}\text{O}$ are also moderately ($0.4 < p < 0.6$) correlated with $A(^3\text{H})$ and moderately anticorrelated with relative humidity (RH) (Fig. 6). In contrast to other isotopic variables, d-excess shows moderate anticorrelation with T . Gačnik et al. (2026) showed that a ~3-month lag exists between the annual T cycle and the annual d-excess cycle in Central Europe, which complicates the interpretation of the unadjusted correlation between T and d-excess. RH is strongly ($0.6 < p < 0.8$) to moderately anticorrelated with $\delta^2\text{H}$, $\delta^{18}\text{O}$, and $A(^3\text{H})$ which is in line with dry (low RH) atmospheric conditions causing increased evaporation and therefore heavier isotopic composition of precipitation. Correlations of $A(^3\text{H})$ with T are not as strong as for $\delta^2\text{H}$ or $\delta^{18}\text{O}$ with T , likely due to the radioactive decay of the background atmospheric ^3H masking the influence of T . All variables are at best weakly correlated with P , indicating its limited influence.

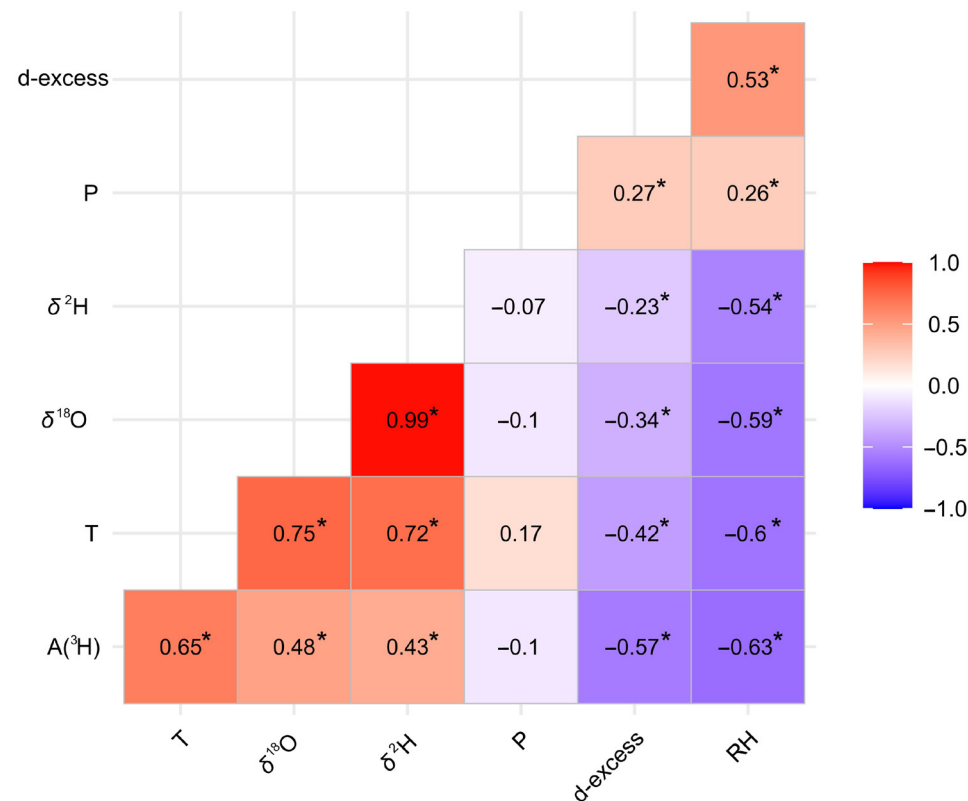


Fig. 6. Pearson correlation matrix of the isotopic and ancillary variables for the Ljubljana dataset (whole 2011–2024 period correlations).

Conclusions

Air temperatures in Ljubljana are rising, and although mean precipitation amounts are not higher than in previous investigations of the Ljubljana dataset, extreme precipitation events are becoming more frequent. These meteorological changes are also reflected in the isotopic composition of precipitation in Ljubljana with temperature variations still being the primary driver of isotopic composition. Precipitation amount does not substantially influence the mean isotopic values; however, extremely low precipitation amounts are responsible for the majority of isotopic extremes observed in the investigated dataset.

Precipitation-weighted means of $\delta^{18}\text{O}$, $\delta^2\text{H}$, d-excess, and $A(^3\text{H})$ in Ljubljana (Reaktor) were not affected by the choice of precipitation amount data, as collocated data and data collected at a nearby station, Ljubljana (Bežigrad) did not result in statistically significant differences between precipitation-weighted means of any of the investigated variables.

Yearly and seasonal cycles of $\delta^{18}\text{O}$ and $\delta^2\text{H}$ follow the temperature cycle, whereas the interpretation of d-excess seasonality is less straightforward and requires advanced statistical methods. Nevertheless, the autumn maximum of d-excess in Ljubljana has been shown to be driven by precipitation of Mediterranean origin (Gačnik et al., 2026). The radioactive decay of the nuclear-test-

ing background of ^3H over time has lowered the baseline of $A(^3\text{H})$, thereby enabling the detection of seasonal cycles driven by natural processes, such as the spring rise of the troposphere and solar minima and maxima, which were previously mostly obscured.

As the dataset lengthens, increasingly reliable information will be obtainable on the basis of robust statistical analyses. Therefore, it is crucial that monitoring within the SLONIP programme continues uninterrupted over the long term.

Data Availability Statement

Data analysis and visualization was done in R version 4.4.2 (R Core Team, 2021). Post-processing of figures and creation of the graphical abstract were done in Inkscape version 1.4. All data analysis and visualization scripts are available at the GitHub repository (https://github.com/jgacnik/Geologija_data_analysis).

Acknowledgements

This research was funded by the Slovenian Research and Innovation Agency (ARIS; research programs P1-0143 and P2-0075, 2011–2026 and bilateral research project N1-0054, 2016–2018), the EU Partnership Agriculture of Data and the International Atomic Energy Agency (CRP F33024, CRP F31006, RER7013, RER7017, NC SLO7001). Special thanks are due to S.

Žigon, A. Leis, S. Lindbichler, S. Terzer-Wassmuth, I. Krajcar Bronić, J. Barešić, B. Svetek and V. Stibilj for their valuable help with analyses. We also thank M. Demšar for providing meteorological data for automatic station Hrastje.

References

- Araguás-Araguás, L., Froehlich, K. & Rozanski, K. 2000: Deuterium and oxygen-18 isotope composition of precipitation and atmospheric moisture. *Hydrological Processes*, 14/81341–1355. [https://doi.org/10.1002/1099-1085\(2000615\)14:8<1341::AID-HYP983>3.0.CO;2-Z](https://doi.org/10.1002/1099-1085(2000615)14:8<1341::AID-HYP983>3.0.CO;2-Z)
- Avak, H. & Brand, W.A. 1995: The Finning MAT HDO-Equilibration-A fully automated H₂O/gas phase equilibration system for hydrogen and oxygen isotope analyses. *Thermo Electron. Corp. Appl. News*, 11: 1–13.
- Barešić, J., Horvatinčić, N., Krajcar Bronić, I. & Obelić, B. 2010: Comparison of two techniques for low-level tritium measurement-Gas proportional and liquid scintillation counting. *Proceedings of the Third European IRPA Congress*, Helsinki, Finland, 14–18.
- Barešić, J., Horvatinčić, N., Krajcar Bronić, I. & Sironić, A. 2013: Stability analysis of Systems for preparation and measurement of 3H and 14C. *Proceedings of 9th Symposium of the Croatian Radiation Protection Association*, INIS-HR--13001, 495–501.
- Barešić, J., Krajcar Bronić, I., Horvatinčić, N., Obelić, B., Sironić, A. & Kožar-Logar, J. 2011: Tritium Activity Measurement of Water Samples Using Liquid Scintillation Counter and Electrolytical Enrichment. *Proceedings of 8th Symposium of the Croatian Radiation Protection Association*, 461–467.
- Bezjak, N., Sapač, K., Sečnik, M., Lojen, S., Petrič, M. & Rusjan, S. 2017: Applications of stable oxygen and hydrogen isotopes in hydrological research: Slovenian experience. *Acta Hydro-technica*, 30/52: 15–35.
- Brenčič, M., Kononova, N.K. & Vreča, P. 2015: Relation between isotopic composition of precipitation and atmospheric circulation patterns. *Journal of Hydrology*, 529: 1422–1432. <https://doi.org/10.1016/j.jhydrol.2015.08.040>
- Brkić, Ž., Kuhta, M., Hunjak, T. & Larva, O. 2020: Regional isotopic signatures of groundwater in Croatia. *Water*, 12/7. <https://doi.org/10.3390/w12071983>
- Brkić, Ž., Larva, O. & Kuhta, M. 2021: Groundwater age as an indicator of nitrate concentration evolution in aquifers affected by agricultural activities. *Journal of Hydrology*, 602. <https://doi.org/10.1016/j.jhydrol.2021.126799>
- Bundesministerium für Land-und Forstwirtschaft. (n.d.). The ANIP database. Retrieved April 2, 2025, from <https://wasser.umweltbundesamt.at/h2odb/>
- Carey, A.E., Zorn, M., Tičar, J., Lipar, M., Komac, B., Welch, S.A., Smith, D.F. & Lyons, W.B. 2019: Glaciochemistry of cave Ice: Paradana and Snežna Caves, Slovenia. *Geosciences*, 9/2: 1–12. <https://doi.org/10.3390/geosciences9020094>
- Coplen, T.B. 1995: Reporting of stable hydrogen, carbon, and oxygen isotopic abundances. *Geothermics*, 24/5:707–712. [https://doi.org/10.1016/0375-6505\(95\)00024-0](https://doi.org/10.1016/0375-6505(95)00024-0)
- Coplen, T.B., Wildman, J.D. & Chen, J. 1991: Improvements in the gaseous hydrogen-water equilibration technique for hydrogen isotope-ratio analysis. *Analytical Chemistry*, 63/9: 910–912. <https://doi.org/10.1021/ac00009a014>
- Crawford, J., Hughes, C.E. & Lykoudis, S. 2014: Alternative least squares methods for determining the meteoric water line, demonstrated using GNIP data. *Journal of Hydrology*, 519(PB): 2331–2340. <https://doi.org/10.1016/j.jhydrol.2014.10.033>
- Dansgaard, W. 1964: Stable isotopes in precipitation. *Tellus A: Dynamic Meteorology and Oceanography*, 16/4: 436–468. <https://doi.org/10.3402/tellusa.v16i4.8993>
- Domínguez-Villar, D., Lojen, S., Krklec, K., Kozdon, R., Edwards, R. L. & Cheng, H. 2018: Ion microprobe $\delta^{18}\text{O}$ analyses to calibrate slow growth rate speleothem records with regional $\delta^{18}\text{O}$ records of precipitation. *Earth and Planetary Science Letters*, 482: 367–376. <https://doi.org/10.1016/j.epsl.2017.11.012>
- Epstein, S. & Mayeda, T. 1953: Variation of O¹⁸ content of waters from natural sources. *Geochimica et Cosmochimica Acta*, 4/5: 213–224. [https://doi.org/10.1016/0016-7037\(53\)90051-9](https://doi.org/10.1016/0016-7037(53)90051-9)
- Filipović, V., Kovač, Z., Kopic, J., Nakić, Z., Parlov, J. & Skopljak, F. 2022: Isotopic signature of the Sikirevci well field and its connection with the Sava River. *Mathematical Methods and Terminology in Geology 2022: 4th Croatian Scientific Congress about Geomathematics and Terminology in Geology*, 115–122.
- Gačnik, J., Žagar, K., Hatvani, I. G., Kern, Z. & Vreča, P. 2026: Climate change reflected in 40-year isotopic composition trends of precipitation in Slovenia. *Environmental Research*, 288, 123286. <https://doi.org/10.1016/j.envres.2025.123286>

- Gat, J.R. 1996: Oxygen and hydrogen isotopes in the hydrologic cycle. *Annual Review Of Earth And Planetary Sciences*, 24: 225–262. <https://doi.org/10.1146/annurev.earth.24.1.225>
- Gat, J.R., Bowser, C.J. & Kendall, C. 1994: The contribution of evaporation from the Great Lakes to the continental atmosphere: estimate based on stable isotope data. *Geophysical Research Letters*, 21/7: 557–560. <https://doi.org/10.1029/94GL00069>
- Gourcy, L.L., Groening, M. & Aggarwal, P.K. 2005: Stable oxygen and hydrogen isotopes in precipitation. In: Aggarwal, P.K., Gat, J.R. & Froehlich, K.F.O. (eds.): *Isotopes in the Water Cycle: Past, Present and Future of a Developing Science*, 39–51. Springer Dordrecht. <https://doi.org/10.1007/1-4020-3023-1>
- Hager, B. & Foelsche, U. 2015: Stable isotope composition of precipitation in Austria. *Austrian Journal of Earth Sciences*, 108/2: 2–14. <https://doi.org/10.17738/ajes.2015.0012>
- Harvey, F.E. 2005: Stable hydrogen and oxygen isotope composition of precipitation in Northeastern Colorado. *JAWRA Journal of the American Water Resources Association*, 41/2: 447–460. <https://doi.org/10.1111/j.1752-1688.2005.tb03748.x>
- Hatvani, I.G., Smati, A.E., Erdélyi, D., Szatmári, G., Vreča, P. & Kern, Z. 2023: Modeling the spatial distribution of the meteoric water line of modern precipitation across the broader Mediterranean region. *Journal of Hydrology*, 617, B. <https://doi.org/10.1016/j.jhydrol.2022.128925>
- Hatvani, I.G., Szatmári, G., Kern, Z., Erdélyi, D., Vreča, P., Kanduč, T., Czuppon, G., Lojen, S. & Kohán, B. 2021: Geostatistical evaluation of the design of the precipitation stable isotope monitoring network for Slovenia and Hungary. *Environment International*, 146. <https://doi.org/10.1016/j.envint.2020.106263>
- Hughes, C.E. & Crawford, J. 2012: A new precipitation weighted method for determining the meteoric water line for hydrological applications demonstrated using Australian and global GNIP data. *Journal of Hydrology*, 464–465, 344–351. <https://doi.org/10.1016/j.jhydrol.2012.07.029>
- Hyndman, R.J. & Khandakar, Y. 2008: Automatic time series forecasting: the forecast package for R. *Journal of Statistical Software*, 27/3: 1–22. <https://doi.org/10.18637/jss.v027.i03>
- IAEA 1992: *Statistical Treatment of Environmental Isotope Data in Precipitation*. Technical Report Series No. 331.
- International Atomic Energy Agency & World Meteorological Organization (n.d.): *Global Network of Isotopes in Precipitation*. The GNIP Database. Retrieved April 21, 2022, from <https://nucleus.iaea.org/wiser>
- Jožef Stefan Institute 2020: *SLONIP: Slovenian Network of Isotopes in Precipitation*. <https://slonip.ijs.si/>
- Kanduč, T., Šlejkovec, Z., Vreča, P., Samardžija, Z., Verbovšek, T., Božič, D., Jamnikar, S., Solomon, D.K., Fernandez, D.P., Eastoe, C., McIntosh, J., Mori, N. & Grassa, F. 2019: The effect of geochemical processes on groundwater in the Velenje coal basin, Slovenia: insights from mineralogy, trace elements and isotopes signatures. *SN Applied Sciences*, 1/11: 1–30. <https://doi.org/10.1007/s42452-019-1561-6>
- Kassambara, A. 2023: ggcorrplot: Visualization of a Correlation Matrix using “ggplot2.” <https://cran.r-project.org/package=ggcorrplot>
- Kern, Z., Erdélyi, D., Vreča, P., Krajcar Bronić, I., Forizs, I., Kandu, T., Štrok, M., Palcsu, L., Suveges, M., Czuppon, G., Kohan, B. & Hatvani, I.G. 2020: Isoscape of amount-weighted annual mean precipitation tritium (^3H) activity from 1976 to 2017 for the Adriatic-Pannonian region - AP3H_v1 database. *Earth System Science Data*, 12/3: 2061–2073. <https://doi.org/10.5194/essd-12-2061-2020>
- Kern, Z., Hatvani, I. G., Czuppon, G., Fórizs, I., Erdélyi, D., Kanduč, T., Palcsu, L. & Vreča, P. 2020: Isotopic “altitude” and “continental” effects in modern precipitation across the Adriatic-Pannonian region. *Water (Switzerland)*, 12/6. <https://doi.org/10.3390/w12061797>
- Krajcar Bronić, I., Barešić, J., Borković, D., Sironić, A., Mikelić, I.L. & Vreča, P. 2020: Long-Term isotope records of precipitation in Zagreb, Croatia. *Water*, 12/1: <https://doi.org/10.3390/w12010226>
- Krajcar Bronić, I., Barešić, J., Sironić, A., Mikelić, I.L., Borković, D., Horvatinčić, N. & Kovač, Z. 2020: Isotope composition of precipitation, groundwater, and surface and lake waters from the Plitvice lakes, Croatia. *Water*, 12/9:1–26. <https://doi.org/10.3390/W12092414>
- Lancaster, S.T., Irrgeher, J., Dallmayr, R., Conrad, E., Hörhold, M., Bohleber, P., Behrens, M., Camin, F., Žagar, K., Vreča, P. & Prohaska, T. 2025: $\delta(^{18}\text{O}/^{16}\text{O})$ Determinations in Water Using Inductively Coupled Plasma–Tandem Mass Spectrometry. *Analytical Chemistry*. <https://doi.org/10.1021/acs.analchem.5c02607>
- Leskovar, T., Snoeck, C., Črešnar, M., Hlad, M., Gerritzen, T.C., James, H.F., Spros, R., Goderis,

- S. & Gaspari, A. 2025: Colonia Iulia Emona at the crossroads in the South-Eastern Alpine region during the late Roman period – An isotope perspective. *Journal of Archaeological Science: Reports*, 65. <https://doi.org/10.1016/j.jas-rep.2025.105218>
- Massicotte, P. & South, A. 2025: rnaturalearth: World Map Data from Natural Earth. <https://cran.r-project.org/package=rnaturalearth>
- Mezga, K., Urbanc, J. & Cerar, S. 2014: The isotope altitude effect reflected in groundwater: A case study from Slovenia. *Isotopes in Environmental and Health Studies*, 50/1: 33–51. <https://doi.org/10.1080/10256016.2013.826213>
- Morrison, J., Brockwell, T., Merren, T., Fourel, F. & Phillips, A.M. 2001: On-Line High-Precision Stable Hydrogen Isotopic Analyses on Nanoliter Water Samples. *Analytical Chemistry*, 73/15: 3570–3575. <https://doi.org/10.1021/ac001447t>
- Mulec, J., Oarga-Mulec, A., Holko, L., Pašić, L., Kopitar, A.N., Eleršek, T. & Mihevc, A. 2021: Microbiota entrapped in recently-formed ice: Paradana Ice Cave, Slovenia. *Scientific Reports*, 11/1: 1–12. <https://doi.org/10.1038/s41598-021-81528-6>
- Nagode, K., Kanduč, T., Lojen, S., Železnik, B.B., Jamnik, B. & Vreča, P. 2020: Synthesis of past isotope hydrology investigations in the area of Ljubljana, Slovenia. *Geologija*, 63/2: 261–270. <https://doi.org/10.5474/geologija.2020.019>
- Nagode, K., Kanduč, T., Železnik, B.B., Jamnik, B. & Vreča, P. 2022: Multi-Isotope Characterization of Water in the Water Supply System of the City of Ljubljana, Slovenia. *Water*, 14/13: 1–16. <https://doi.org/10.3390/w14132064>
- Nagode, K., Pavšek, A., Pavlič, U. & Vreča, P. 2022: Izotopska sestava padavin in reke Save na območju Ljubljanskega polja med leti 2020 in 2021. In: Kuhar, M., Vreča, P., Zupančič, P., Čarman, M., Šraj, M., Triglav Čekada, M., Skok, G., Ličer, M., Stopar, B. & Čop, R. (eds.): *Raziskave s področja geodezije in geofizike 2021*, 65–77.
- Ogrinc, N., Kocman, D., Miljević, N., Vreča, P., Vrzal, J. & Povinec, P. 2018: Distribution of H and O stable isotopes in the surface waters of the Sava River, the major tributary of the Danube River. *Journal of Hydrology*, 565: 365–373. <https://doi.org/10.1016/j.jhydrol.2018.08.024>
- Palcsu, L., Morgenstern, U., Sültenfuss, J., Koltai, G., László, E., Temovski, M., Major, Z., Nagy, J.T., Papp, L., Varlam, C., Faurescu, I., Túri, M., Rinyu, L., Czuppon, G., Bottyán, E. & Jull, A. J.T. 2018: Modulation of Cosmogenic Tritium in Meteoric Precipitation by the 11-year Cycle of Solar Magnetic Field Activity. *Scientific Reports*, 8/1: 1–9. <https://doi.org/10.1038/s41598-018-31208-9>
- Parlov, J., Kovač, Z., Nakić, Z. & Barešić, J. 2019: Using water stable isotopes for identifying groundwater recharge sources of the unconfined alluvial Zagreb aquifer (Croatia). *Water*, 11/10. <https://doi.org/10.3390/w11102177>
- Pebesma, E. 2018: Simple features for R: Standardized support for spatial vector data. *R Journal*, 10/1: 439–446. <https://doi.org/10.32614/rj-2018-009>
- Peng, H., Mayer, B., Harris, S. & Krouse, H.R. 2004: A 10-yr record of stable isotope ratios of hydrogen and oxygen in precipitation at Calgary, Alberta, Canada. *Tellus B: Chemical and Physical Meteorology*, 56/2: 147–159. <https://doi.org/10.3402/tellusb.v56i2.16410>
- Pezdič, J. 1999: Izotopi in geokemijski procesi. Naravoslovnotehniška fakulteta, Oddelek za geologijo.
- Pezdič, J. 2003: Isotope Fractionation of Long Term Precipitation Averages in Ljubljana (Slovenia). *RMZ-Materials and Geoenvironment*, 50/3: 641–650. <https://www.dlib.si/stream/URN:NBN:SI:DOC-8SETUQ5O/403f82dd-fe65-4b5b-a9aa-f524902548a4/PDF>
- R Core Team 2021: R: A language and environment for statistical computing. R Foundation for Statistical Computing.
- Racine, T.M.F., Spötl, C., Reimer, P.J. & Čarga, J. 2022: Radiocarbon constraints on periods of positive cave ice mass balance during the last millennium, Julian alps (NW Slovenia). *Radiocarbon*, 64/2: 333–356. <https://doi.org/10.1017/RDC.2022.26>
- Rozanski, K., Araguás-Araguás, L. & Gonfiantini, R. 1993: Isotopic Patterns in Modern Global Precipitation. In: Swart, P.K., Lohmann, K.C., McKenzie, J. & Savin, S. (eds.): *Climate Change in Continental Isotopic Records* (pp. 1–36). American Geophysical Union (AGU). <https://doi.org/10.1029/GM078p0001>
- Rozanski, K., Gonfiantini, R. & Araguas-Araguas, L. 1991: Tritium in the global atmosphere: Distribution patterns and recent trends. *Journal of Physics G: Nuclear and Particle Physics*, 17(S). <https://doi.org/10.1088/0954-3899/17/S/053>
- Rusjan, S., Sapač, K., Petrič, M., Lojen, S. & Bezak, N. 2019: Identifying the hydrological behavior of a complex karst system using stable isotopes. *Journal of Hydrology*, 577 (November 2018). <https://doi.org/10.1016/j.jhydrol.2019.123956>

- Schirmer, M., Leschik, S. & Musolff, A. 2013: Current research in urban hydrogeology - A review. *Advances in Water Resources*, 51, 280–291. <https://doi.org/10.1016/j.advwatres.2012.06.015>
- Schürch, M., Kozel, R., Schotterer, U. & Tripet, J.P. 2003: Observation of isotopes in the water cycle - The Swiss National Network (NISOT). *Environmental Geology*, 45/1: 1–11. <https://doi.org/10.1007/s00254-003-0843-9>
- Serianz, L., Rman, N. & Brenčič, M. 2020: Hydro-geochemical characterization of a warm spring system in a carbonate mountain range of the eastern Julian Alps, Slovenia. *Water*, 12/5. <https://doi.org/10.3390/w12051427>
- Slovenian Environmental Agency (ARSO). (2025). ARSO METEO.
- Smith, D.F., Lyons, W.B., Welch, S.A., Zorn, M., Tičar, J., Lipar, M. & Carey, A.E. 2023: The Chemistry of Cave Ice: Two Examples from Slovenia. *Environmental and Engineering Geoscience*, 29/4: 291–307. <https://doi.org/10.21663/EEG-D-23-00001>
- Torkar, A., Brenčič, M. & Vreča, P. 2016: Chemical and isotopic characteristics of groundwater-dominated Radovna River (NW Slovenia). *Environmental Earth Sciences*, 75/18. <https://doi.org/10.1007/s12665-016-6104-5>
- Trček, B. & Mesarec, B. 2023: Impact of the Hydroelectric Dam on Aquifer Recharge Processes in the Krško Field and the Vrbina Area: Evidence from Hydrogen and Oxygen Isotopes. *Water*, 15/3. <https://doi.org/10.3390/w15030412>
- Vreča, P., Kanduč, T., Kocman, D., Lojen, S., Robinson, J.A. & Štok, M. 2017: Slovenska mreža opazovanj izotopske sestave padavin (SLONIP): pregled in možnost uporabe pri upravljanju z vodnimi viri. In: Globevnik, L. & Širca, A. (eds.): *Drugi slovenski kongres o vodah* (pp. 225–234).
- Vreča, P., Kanduč, T., Štok, M., Žagar, K., Nigro, M. & Barsanti, M. 2024: An Assessment of Six Years of Precipitation Stable Isotope and Tritium Activity Concentration Records at Station Sv. Urban, Eastern Slovenia. *Water*, 16/3. <https://doi.org/10.3390/w16030469>
- Vreča, P., Krajcar Bronić, I., Leis, A. & Brenčič, M. 2008: Isotopic composition of precipitation in Ljubljana (Slovenia). *Geologija*, 51/2: 169–180. <https://doi.org/10.5474/geologija.2008.018>
- Vreča, P., Krajcar Bronić, I., Leis, A. & Demšar, M. 2014: Isotopic composition of precipitation at the station Ljubljana (Reaktor), Slovenia - period 2007–2010. *Geologija*, 57/2: 217–230. <https://doi.org/10.5474/geologija.2014.019>
- Vreča, P. & Malenšek, N. 2016: Slovenian Network of Isotopes in Precipitation (SLONIP) - a review of activities in the period 1981–2015. *Geologija*, 59/1: 67–84. <https://doi.org/10.5474/geologija.2016.004>
- Vreča, P. & Pavšek, A. 2022: Slovenska mreža opazovanj izotopske sestave padavin (SLONIP) – predstavitev spletne strani <https://slonip.ijs.si/>. In: Kuhar, M., Vreča, P., Zupančič, P., Čarman, M., Šraj, M., Triglav Čekada, M., Skok, G., Ličer, M., Stopar, B. & Čop, R. (eds.): *Raziskave s področja geodezije in geofizike 2021*: 65–77.
- Vreča, P., Pavšek, A. & Kocman, D. 2022: SLO-NIP—A Slovenian Web-Based Interactive Research Platform on Water Isotopes in Precipitation. *Water*, 14/13. <https://doi.org/10.3390/w14132127>
- Vreča, P., Pavšek, A. & Kocman, D. 2023: SLONIP – Slovenska spletna platforma za interaktivno raziskovanje podatkov o izotopski sestavi padavin. In: Globevnik, L. & Širca, A. (eds.): *Tretji slovenski kongres o vodah*, 357–363.
- Vreča, P., Štok, M., Žigon, S. & Svetek, B. 2017: WORKING REPORT: Isotope composition of precipitation at stations Ljubljana-Portorož airport: period 2011–2015 (IJS Delovno Poročilo, 12383).
- Vreča, P. & Žigon, S. 2016: WORKING REPORT: Poročilo o določitvi izotopske sestave vodika in kisika v vzorcih WICO 2016 z masnim spektrometrom Finnian MAT DELTA plus (IJS Delovno Poročilo, 12166).
- Wassenaar, L.I., Coplen, T.B. & Aggarwal, P.K. 2014: Approaches for Achieving Long-Term Accuracy and Precision of $\delta^{18}\text{O}$ and $\delta^2\text{H}$ for Waters Analyzed using Laser Absorption Spectrometers. *Environmental Science & Technology*, 48/2: 1123–1131. <https://doi.org/10.1021/es403354n>
- Wickham, H., Averick, M., Bryan, J., Chang, W., McGowan, L.D., François, R., Grolemund, G., Hayes, A., Henry, L., Hester, J., Kuhn, M., Pedersen, T.L., Miller, E., Bache, S.M., Müller, K., Ooms, J., Robinson, D., Seidel, D.P., Spinu, V. & Yutani, H. 2019: Welcome to the Tidyverse. *Journal of Open Source Software*, 4/43: 1686. <https://doi.org/10.21105/joss.01686>
- Wickham, H. & Bryan, J. 2025: readxl: Read Excel Files. <https://cran.r-project.org/package=readxl>
- Winter, T. 2019: Hydrochemistry and isotope hydrology of thermal springs in the Alps. Master Thesis. Georg-August-Universität Göttingen. <https://www.uni-goettingen.de/de/document/download/bb10b21f3b5ddba8e->

[26ab29be97087a7.pdf/Masterarbeit_Hydro-chemistry_Isotope_ThermalSprings_Alps_TheisWinter.pdf](#)

Žagar, K., Ortega, L., Pavlič, U., Jamnik, B., Bračič Železnik, B. & Vreča, P. 2024: Unravelling the

sources contributing to the urban water supply: An isotope perspective from Ljubljana, Slovenia. *Journal of Hydrology*, 632. <https://doi.org/10.1016/j.jhydrol.2024.130892>