

Analysis of the Stable Isotopic Composition of Precipitation in Uzbekistan Using Different Regression Methods

Serik Isabekov¹; Bakhriddin Nishonov^{1,2}; Utkir Balxiev³; Bekhzod Nishonov³; Tamara Marković⁴

¹Hydrometeorological Research Institute, Tashkent, Uzbekistan;

<https://orcid.org/0009-0006-4717-1431>

²Central Asian University of Environmental and Climate Change Studies (Green University), Tashkent, Uzbekistan;

<https://orcid.org/0000-0002-7407-1341>

³Hydrometeorological Research Institute, Tashkent, Uzbekistan

⁴Croatian Geological Survey, Milana Sachsa 2, Zagreb, Croatia;

<https://orcid.org/0000-0003-0572-0376>

Corresponding author: tmarkovic@hgi-cgs.hr

Abstract

Stable isotopes $\delta^{18}\text{O}$ and $\delta^2\text{H}$ are widely used as tracers for investigating hydrological processes, including groundwater recharge, evaporation, and surface water–groundwater interactions. This study evaluates the isotopic composition of precipitation in Uzbekistan, using data from six Global Network of Isotopes in Precipitation (GNIP) stations. Local Meteoric Water Lines (LMWLs) were established using six different regression methods and compared with the Global Meteoric Water Line (GMWL) to assess regional isotope variability and the influence of climatic and geographic factors. The results reveal considerable spatial variability in isotopic composition of precipitation across Uzbekistan. Most LMWLs closely follow the GMWL, indicating that equilibrium condensation is the dominant isotope-fractionation process. Mountain stations exhibit higher slopes and intercepts, reflecting reduced evaporation effects and stronger orographic influences, whereas lowland stations show evidence of enhanced evaporative enrichment. These spatial variations are primarily controlled by altitude, continentality, and local climatic conditions. The derived LMWLs provide an important reference framework for future hydrological, hydrogeological, and climate-related investigations in Uzbekistan and contribute to a better understanding of regional water-cycle processes.

Keywords: $\delta^{18}\text{O}$ and $\delta^2\text{H}$, correlation, precipitation, GNIP stations, Uzbekistan

1. Introduction

Stable isotopes of oxygen-18 ($\delta^{18}\text{O}$) and hydrogen-2 ($\delta^2\text{H}$) are among the most important tracers used in hydrological research (Araguás-Araguás et al., 2000; Aemisegger et al., 2014; Bowen et al., 2019; Vreča & Kern, 2020). Variations in their isotopic composition provide valuable information about evaporation, condensation, moisture transport pathways, groundwater recharge, and interactions between surface water and groundwater (Benettin et al., 2015; Krajcar Bronić et al., 2020; Marković et al., 2020; Kovač et al., 2022; Cui et al., 2025). Consequently, isotope hydrology has become an essential tool for understanding regional and global water cycles. The relationship between hydrogen and oxygen isotopes in global precipitation was first described by Craig (1961), who established the Global Meteoric Water Line (GMWL) (Equation 1):

$$\delta^2\text{H} = 8\delta^{18}\text{O} + 10 \quad (1)$$

where $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values are expressed relative to Vienna Standard Mean Ocean Water (VSMOW). The slope and intercept of the GMWL reflect equilibrium fractionation processes occurring during condensation and precipitation.

However, local climatic and geographical conditions often cause deviations from the global relationship. Factors such as temperature, humidity, continentality, altitude, and evaporation may significantly modify the isotopic composition of precipitation. Therefore, Local Meteoric Water Lines (LMWLs) are commonly established to describe regional isotope characteristics more accurately. LMWLs are particularly valuable in hydrogeological investigations because they reflect local precipitation conditions and facilitate the identification of groundwater recharge sources and other hydrological processes.

The Global Network of Isotopes in Precipitation (GNIP), jointly operated by the International Atomic Energy Agency (IAEA) and the World Meteorological Organization (WMO), represents the largest international database of precipitation isotope measurements (IAEA, 2026). Established in 1961, the GNIP program provides long-term observations of precipitation isotopic composition worldwide and facilitates the development of regional LMWLs. These data have significantly improved our understanding of atmospheric moisture sources and climate controls on precipitation isotopes.

Although numerous isotope studies have been conducted worldwide, Central Asia remains relatively poorly investigated (Saidaliyeva et al., 2024). Uzbekistan, characterized by strong continentality and arid climatic conditions, represents an important region for isotope hydrology due to increasing water scarcity and growing impacts of climate change. The objective of this study is to establish and compare LMWLs for selected GNIP stations in Uzbekistan using six regression methods and to evaluate spatial differences of precipitation isotopes across the country.

2. Study area

Uzbekistan is located in Central Asia between approximately 37° and 45° N latitude and 56° and 73° E longitude (**Figure 1**). The country is characterized by predominantly arid and semi-arid climatic conditions, with a strong continental influence resulting from its distance from major oceanic moisture sources. The climate of Uzbekistan is characterized by hot, dry summers and cold winters. Annual precipitation generally decreases from mountainous regions toward lowland desert areas and exhibits pronounced seasonal variability (**Figure 2**). Most precipitation occurs during winter and spring, while summers are typically dry. These climatic gradients strongly influence the isotopic composition of precipitation throughout the region.

This study focuses on six GNIP stations distributed across different geographic and climatic settings: Tashkent, Angren, Bashkizilsay, Fergana, Samarkand, and Shakhrisabz (**Figure 1**). These stations span a broad range of altitudes and climatic conditions, enabling assessment of spatial variability of precipitation isotopes across Uzbekistan. The dataset used in this study covers the period from 2022 until 2025.

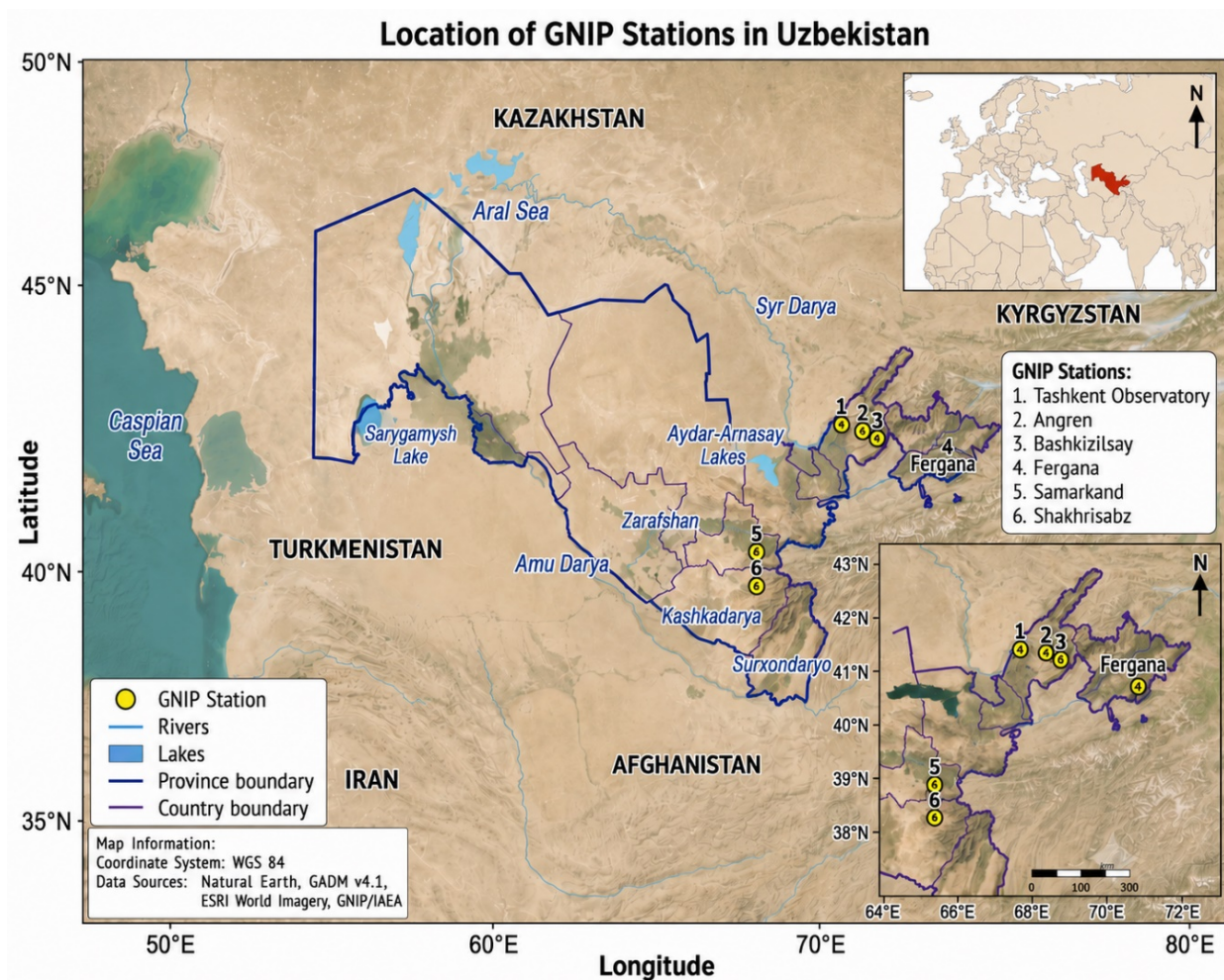


Figure 1: Study area and GNIP stations in Uzbekistan

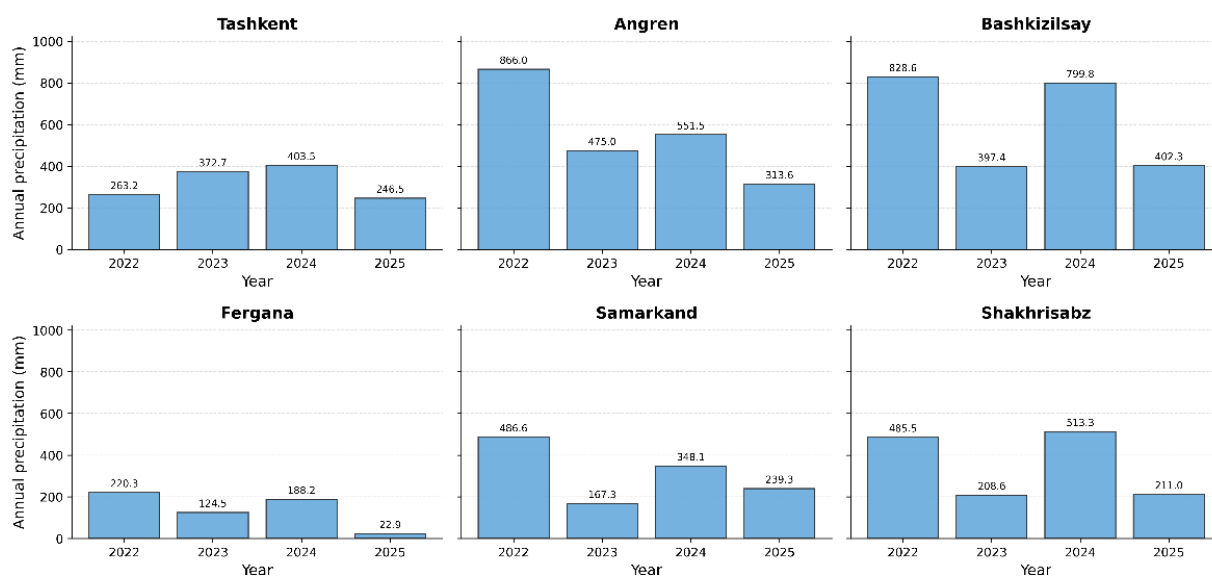


Figure 2: Precipitation amount at six GNIP stations for period 2022-2025

3. Methods

Local Meteoric Water Lines (LMWLs) were established using precipitation isotope data obtained from the GNIP database. Six regression methods were applied to investigate differences in calculated LMWLs:

- Ordinary Least Squares Regression (OLSR);
- Reduced Major Axis Regression (RMA);
- Major Axis Regression (MA);
- Precipitation-Weighted Least Squares Regression (PWLSR);
- Precipitation-Weighted Reduced Major Axis Regression (PWRMA);
- Precipitation-Weighted Major Axis Regression (PWMA).

The regressions were calculated using the Local Meteoric Water Line Freeware developed by **Crawford et al. (2014)**. The software calculates the slope, intercept, standard deviations, and root mean square errors for each regression method and facilitates comparison among them.

LMWLs were defined according to (**Equation 2**):

$$\delta^2\text{H} = a\delta^{18}\text{O} + b \quad (2)$$

where: a is the slope of the regression line; b is the intercept.

The performance of the different regression method was evaluated using the root mean square error and by comparison with the Global Meteoric Water Line (GMWL).

4. Results and discussion

The majority of stations exhibit slopes close to the global value of 8, suggesting that equilibrium condensation is the dominant isotope-fractionation process (**Table 1**). Stations such as Shakhrisabz and Bashkizilsay display slopes exceeding 8, which may indicate limited evaporative enrichment and stronger orographic effects. Intercept values vary considerably among stations, ranging from approximately 3‰ in Fergana to more than 18‰ in Shakhrisabz. Higher intercepts generally correspond to greater deuterium excess and may reflect stronger contributions of continental moisture recycling. The results also demonstrate that precipitation-weighted regressions generally produce slightly higher slopes and intercepts compared with unweighted methods, emphasizing the importance of intense precipitation events in defining LMWLs (**Figure 3**).

Mountain stations, particularly Shakhrisabz and Bashkizilsay, exhibit higher slopes and intercepts, reflecting cooler temperatures, reduced secondary evaporation, and enhanced orographic precipitation processes. Conversely, lowland stations such as Tashkent and Fergana display lower slopes and intercepts, suggesting greater evaporative enrichment of falling raindrops under warm and dry atmospheric conditions, which are characteristic of arid environments. These spatial patterns are consistent with previous isotope studies in Central Asia, where isotopic enrichment during warm seasons and depletion during winter have been attributed to continentality and seasonal temperature variations (**Saidaliyeva et al., 2024**).

Table 1: Calculated Local Meteoric Water Lines by OLSR method for GNIP stations in Uzbekistan

Stations	Latitude	Altitude	Elevations of stations m.a.s.l.	LMWL Equation
Tashkent	41°19'	69°17'	467	$\delta^2\text{H} = 7.46\delta^{18}\text{O} + 6.30$
Angren	41°00'	70°05'	945	$\delta^2\text{H} = 7.93\delta^{18}\text{O} + 15.16$
Bashkizilsay	41°17'	69°40'	1272	$\delta^2\text{H} = 7.93\delta^{18}\text{O} + 13.90$
Fergana	40°22'	71°46'	582	$\delta^2\text{H} = 7.40\delta^{18}\text{O} + 3.13$
Samarkand	39°38'	66°56'	726	$\delta^2\text{H} = 7.86\delta^{18}\text{O} + 11.07$
Shakhrisabz	39°04'	66°50'	625	$\delta^2\text{H} = 8.22\delta^{18}\text{O} + 18.26$

Seasonal box plots of $\delta^{18}\text{O}$ generally show enriched values during summer and depleted values during winter, reflecting the strong seasonal temperature controls on precipitation isotopes (**Figure 4**). However, no boxplot could be generated for the Shakhrisabz station because precipitation is scarce during the summer months (June–August), resulting in insufficient data for statistical analysis. Similar seasonal cycles have been documented throughout Central Asia (**Saidaliyeva et al., 2024**).

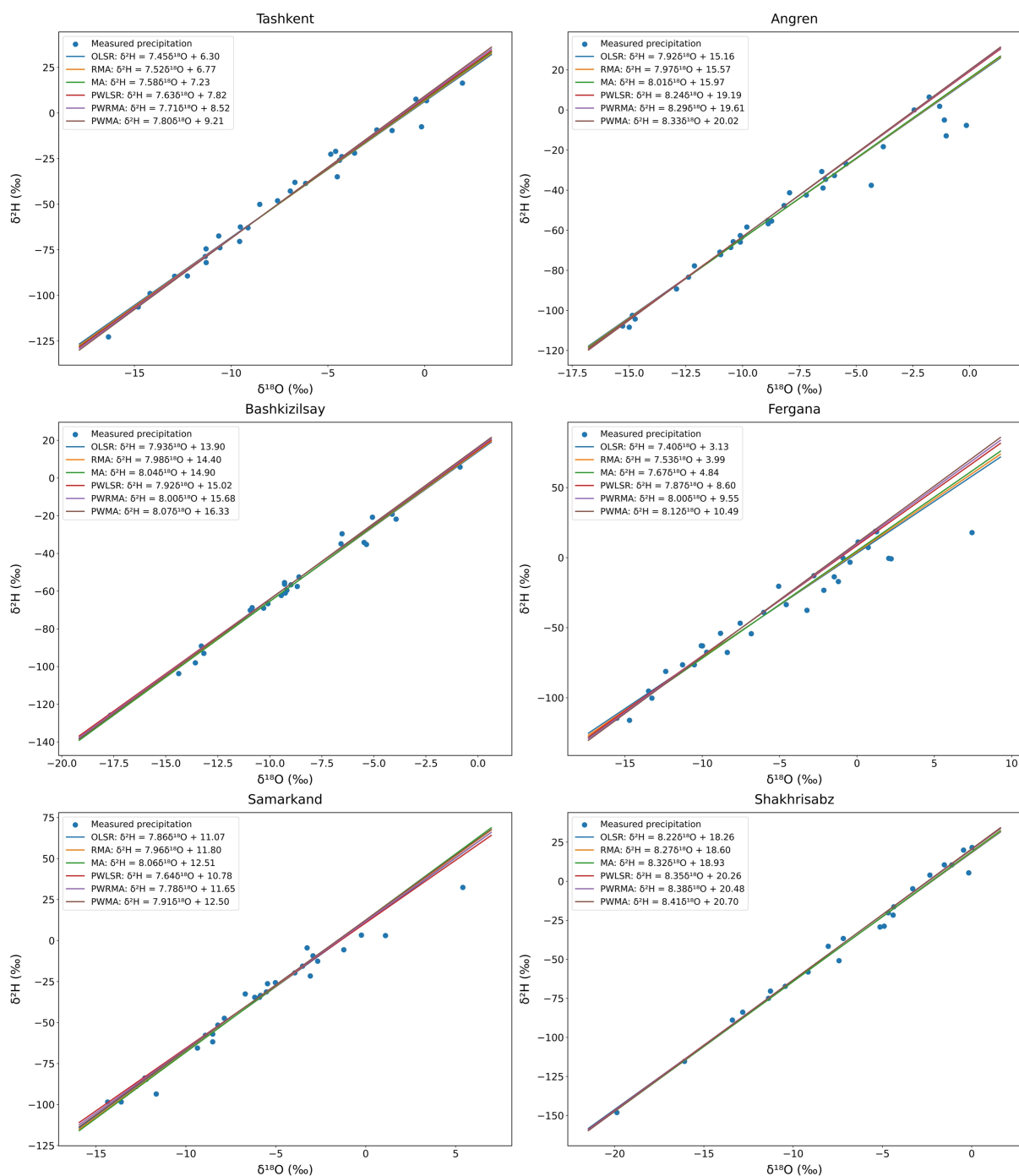


Figure 3: LMWL of GNIP stations

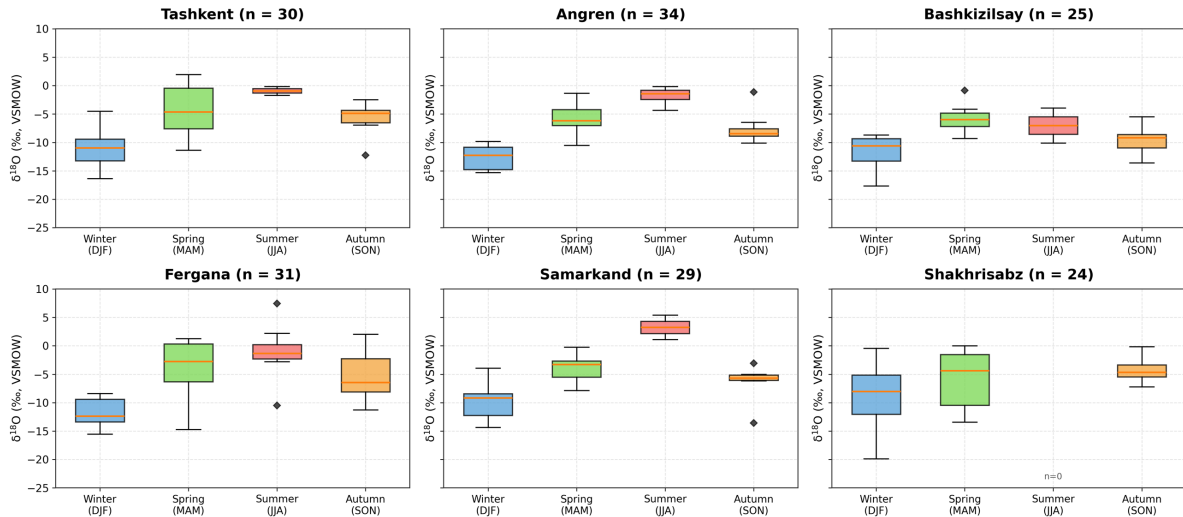


Figure 4: The box plots of $\delta^{18}\text{O}$ in GNIP stations

5. Conclusion

This study investigated the isotopic composition of precipitation at six GNIP stations in Uzbekistan and established LMWLs using six regression methods. The results revealed pronounced spatial variability in the isotopic composition of precipitation across the country. All derived LMWLs closely followed the GMWL, indicating that equilibrium condensation is the dominant isotope-fractionation process. Mountain stations exhibited higher slopes and intercepts, reflecting reduced evaporation and stronger orographic influences, whereas lowland stations showed greater evaporative enrichment. These spatial differences are primarily controlled by altitude, continentality, and local climatic conditions. The derived LMWLs provide a valuable reference framework for future hydrological, hydrogeological, and climate-related studies in Uzbekistan.

6. References

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Abstract in Croatian

Analiza stabilnog izotopnog sastava oborina u Uzbekistanu primjenom različitih regresijskih metoda

Stabilni izotopi $\delta^{18}\text{O}$ i $\delta^2\text{H}$ široko se primjenjuju kao traseri za istraživanje hidroloških procesa, uključujući prihranjivanje podzemnih voda, evaporaciju te međudjelovanje površinskih i podzemnih voda. U ovom se istraživanju procjenjuje izotopni sastav oborina u Uzbekistanu na temelju podataka sa šest postaja Globalne mreže izotopa u oborinama (GNIP). Lokalne meteorske linije voda (LMWL) određene su primjenom šest različitih regresijskih metoda te uspoređene s Globalnom meteorskom linijom voda (GMWL) radi procjene regionalne izotopne varijabilnosti i utjecaja klimatskih i geografskih čimbenika. Rezultati pokazuju izraženu prostornu varijabilnost izotopnog sastava oborina u Uzbekistanu. Većina lokalnih meteorskih linija voda bliska je GMWL-u, što upućuje na to da je ravnotežna kondenzacija dominantan proces izotopne frakcionacije. Planinske postaje pokazuju veće nagibe i odsječke, što odražava smanjenu evaporaciju i izraženije orografske utjecaje, dok nizinske postaje pokazuju znakove pojačenog evaporacijskog obogaćivanja. Te su prostorne razlike prvenstveno uvjetovane nadmorskom visinom, kontinentalnošću i lokalnim klimatskim uvjetima. Dobivene LMWL linije predstavljaju važnu osnovu za buduća hidrološka,

hidrogeološka i klimatska istraživanja u Uzbekistanu te doprinose boljem razumijevanju regionalnih procesa kruženja vode.

Ključne riječi: $\delta^{18}\text{O}$ i $\delta^2\text{H}$, korelacija, oborine, GNIP stanica, Uzbekistan

Author`s contribution

Serik Isabekov: participated in sample collection and paper writing. **Bakhriddin Nishonov:** participated in conceptualization and editing. **Utkir Balxiev:** participated in figures editing. **Bekhzod Nishonov:** participated ins sample collection. **Tamara Marković:** participated in conceptualisation and paper writing.