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Water Stable Isotopes in the Central Altai Mountainous Rivers as Indicator of Glacier Meltwater Fraction in Runoff

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Abstract: We used stable water isotopes ($\delta^{18}O$ and $\delta^{2}H$) to identify the fractions of glacier meltwater and summer precipitation in the runoff in the Taldura River in the Altai mountains. The mean isotopic characteristics of glacier ice, snow, summer precipitation and river water were obtained. Using isotopic separation of hydrographs, we determined that glacier feeding completely prevails throughout the Taldura River in the middle of the ablation season. In general, the fraction of glacier meltwater in the Taldura River's runoff in the ablation season varies from 80% to 95% depending on local weather conditions.

Keywords: stable isotopes; glacier meltwater; glacier rivers; hydrograph separation

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1. Introduction

The main purpose of this study is the estimation of the glacier meltwater fraction in runoff in the Taldura river basin using stable isotope data. This research was carried out on the South-Chuya ridge. The hydrological knowledge of this ridge is extremely insufficient. Currently, most of the gauge stations in the entire Altai Mountains are closed. Closest to the ridge is the Kucherla station on the Kucherla River, located 107 km northwest of the Katunsky ridge in completely different conditions: higher maximal elevation of the ridge, larger amount of precipitation and larger glaciation area. In the Altai region, glacier-originated rivers have a great impact on the economic activities of the local population; therefore, an estimate of the contribution of modern glaciation and other water sources to the runoff is necessary to assess possible changes in the water balance under the conditions of changing climate and deglaciation.

Water stable isotopes (^{18}O and ^{2}H) are currently widely used in upland hydrology. These isotopes in general are used as tracers to identify and estimate water sources. This kind of research is widespread in mainly glaciated mountain territories, especially in the Himalayas [1]. However, such studies have not been carried out practically for the Russian Altai. The complex isotope hydrological studies closest to Altai were carried out on the territory of China at the Urumqi river basin [2], on the Tibetan Plateau [3–6] and in mountainous areas of southwestern China [7]. Isotope studies in Altai are primarily associated with the deep-core drilling of glaciers on the Belukhas plateau [8] and at the Tsambagarav massif in Northwestern Mongolia [9]. For the Altai Mountains and its foothills, isotope analysis of precipitation was performed and compared with model data [10–12].

Earlier, we performed isotope studies at the Tavan-Bogdo-Ola, Tsambagarav and Mongun-Taiga mountain ranges [13,14]. In 2022, the first isotope samples were taken in the Taldura river basin [15].

The Taldura drainage basin belongs to the upper reaches of the unified Ob-Irtysh river system. The isotopic composition of the Ob River in the city of Barnaul was recently investigated [16], but at the same time, isotope data are insufficient in the high mountainous parts of the Ob river basin.

2. Materials and Methods

2.1. Study Area

Isotope hydrological studies were carried out in July–August 2023 in the Taldura River catchment area located in the upper reaches of the Chuya river basin, which is part of the Ob' river basin. The Taldura river originates from the glaciers on the South-Chuya ridge. This ridge is located in the Central Altai and extends from west to east for 120 km. The highest elevation is 3967 m. The South-Chuya ridge is characterized by a large number of glaciers: the total glaciation area is the second largest in the Russian Altai (Figure 1).

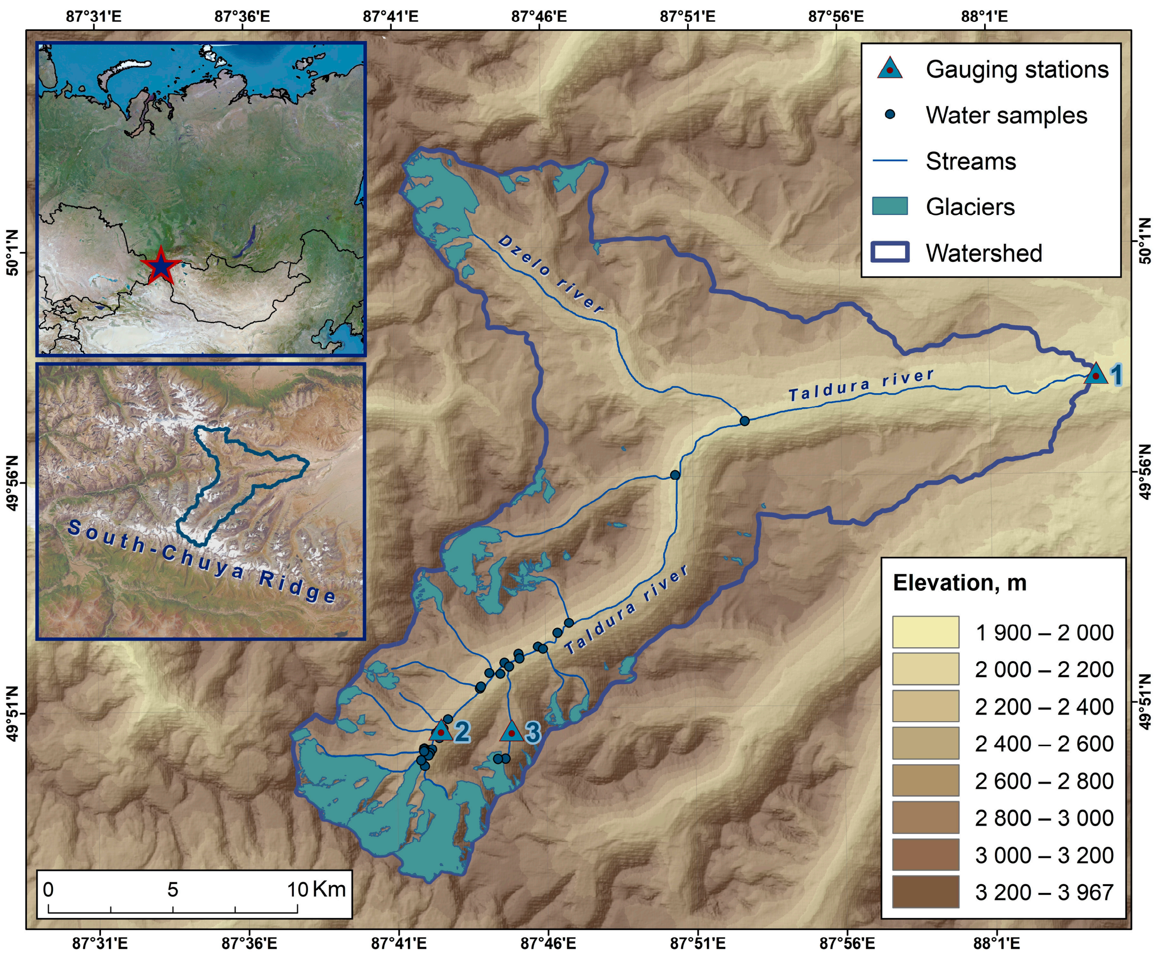

Figure 1. Map of the study area. 1—Lower gauging station. 2—Upper gauging station. 3—Additional gauging station on the tributary.

As a result of climate change, which according to [17] in the territory of the Russian Federation began in the late 1970s, the glaciers of the South-Chuya ridge are shrinking. At the moment, the glaciation area of the South-Chuya Ridge continues to decrease. The total area of glaciers is estimated as 118 km^2. Around 70 glaciers with a total area of 39.8 km^2 are located in the Taldura river basin. The equilibrium line elevation is 3000–3100 m [18]. The Taldura River originates from the Bolshaya Taldura glacier. The river valley is located on the northern macroslope of the South-Chuya ridge (Figure 1). According to the Catalogue of Glaciers of Russia [19], the Bolshaya Taldura glacier system had an area of 20.46 km^2 with a maximum length of 4760 m, a vertical range of 1240 m and an average height of the firn line of 3120 m in 2017.

In this part of Altai, the annual precipitation amount is 400–600 mm. On the windward slopes, it can reach 800–1000 mm. From April to October, 70–85% of the annual precipitation falls. Its monthly maximum is usually observed in June–July [20].

The area of the studied part of the Taldura river basin is 347.8 km^2 (Figure 1). The total glaciation of this part of the basin was estimated at 11.4%.

2.2. Methods

Sample collection was carried out in the middle of the ablation season, from July to August. Most of the samples were taken at the 3 temporary gauging stations (Figure 1). The lower Taldura gauging station was established at an altitude of 1936 m. The upper Taldura gauging station was established at an altitude of 2420 m at a distance of 1600 m from the edge of the Bolshaya Taldura glacier. The observation period at the upper station was 28 days, at the lower one was 18 days. On the right tributary of the Taldura River, at an altitude of 2760 m, the additional gauging station was established. The observation period was 24 days.

At each gauge, the water level was measured 4 times a day and the discharge was also measured periodically. The stage–discharge relation was calculated and for each value of water level, the discharge value was obtained.

At all gauging stations, meteorological observations were also carried out. The air temperature was recorded using the EClerk-M-RHT automatic recorder [21]. The amount of precipitation was determined using a portable rain gauge.

Total dissolved solids (TDS) in water samples was measured by a HANNA HI 98311 Dist5 conductivity meter [22].

Isotope samples at the gauging stations were taken in 50 mL test tubes twice a day: at 08:00 and 20:00. In cases of intense precipitation or high melting, an additional sample was taken, usually at 16:00. Samples of glacier ice, snow, precipitation and different streams were also taken. Glacier ice was collected from the surface of glaciers into plastic bags, then melted at the surrounding temperature and poured into test tubes. The samples from the streams were taken directly into the test tubes. Precipitation was usually sampled twice a day (08:00 and 20:00) from a portable rain gauge.

The relative isotopic composition is indicated by the δ SMOW (standard mean ocean water) and is accepted as the zero standard [23].

$$\delta^{18}O = ([(^{18}O/^{16}O)_{sample} - (^{18}O/^{16}O)SMOW]/(^{18}O/^{16}O)_{SMOW}) \times 10^3 \quad (1)$$

$$\delta^{2}H = ([(^{2}H/H)_{sample} - (^{2}H/H)SMOW]/(^{2}H/H)_{SMOW}) \times 10^3 \quad (2)$$

The analysis of isotopic characteristics was carried out at the Laboratory for Climate and Environmental Change in the Arctic and Antarctic Research Institute (St. Petersburg, Russia) by Cavity Ring-Down Spectroscopy (CRDS) using Picarro L2130-i and Picarro L2140-I analyzers [24]. Distilled tap water from St. Petersburg was used as a laboratory standard, and it had the following characteristics: –9.66 ‰ in $\delta^{18}O$ and –74.1 ‰ in δ^2H relative to the IAEA "V-SMOW2" standard. The measurement precision was 0.04 ‰ for $\delta^{18}O$ and 0.4 ‰ for δ^2H, which is sufficient for this kind of research.

Using stable isotopes as tracers, it is possible to divide the hydrograph into components. The use of stable isotopes in glaciology and hydrology is based on natural differences in the isotopic composition of the water from different sources, e.g., glacier meltwater, groundwater and precipitation. Using only $\delta^{18}O$ values, only two-component separation can be carried out using the isotope balance formula, which generally has the following form:

$$R^{18}O_1 f_1 + R^{18}O_2 f_2 = R^{18}O \quad (3)$$

with $R^{18}O_1$—isotopic content of the first component; f_1—fraction of the first component; $R^{18}O_2$—isotopic content of the second component; f_2—fraction of the second component; $R^{18}O$—resulting isotopic composition [25].

3. Results

3.1. Isotopic Composition of Precipitation

Precipitation samples were taken at different altitudinal levels: at each gauging station and additionally from the surface of the corrie glacier near gauge no. 3 at an elevation of 3000 m. The isotopic composition of the precipitation at every sampling point is shown in Figure 2.

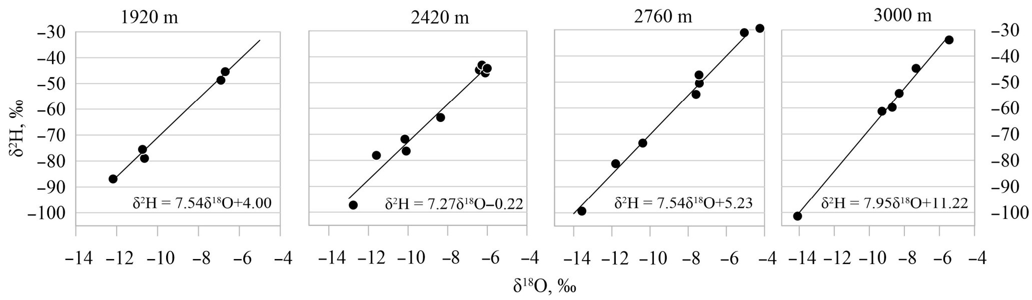

Figure 2. Isotopic composition of the summer precipitation of 2023 at different altitudinal levels.

The local meteoric water line (LMWL) was plotted from the event-based precipitation samples for each elevation separately. The slope of these lines is lower than that of the GMWL, which is common for Inner Asia summer precipitation [13,14,26,27]. The LMWL of the samples from the glacier surface (Figure 2, 3000 m) is close to the GMWL. The weighted-average δ^{18}O of the samples ranges from −8.3‰ to −10.4‰.

The weighted-average δ^{18}O values of ^{18}O were compared with the modeled values from the online calculator OIPC (The Online Isotopes in Precipitation Calculator), which allows the monthly or annual isotopic composition to be calculated using geographical coordinates and elevation (Table 1). This calculator is based on the interpolation of IsoMAP data based on GNIP (Global Network of Isotopes in Precipitation) weather stations [28–30].

Table 1. Comparison of weighted-average δ^{18}O of precipitation in July–August 2023 and OIPC model data (Bowen et al., 2005, Bowen, 2017) [28,29].

	Weighted-Average δ^{18}O, ‰	δ^{18}O in July by OIPC, ‰
Gauge 1, 1920 m	−10.4	−8.3
Gauge 2, 2420 m	−8.3	−8.8
Gauge 3, 2760 m	−9.8	−9.2
Glacier near the gauge 3, 3000 m	−9.3	−9.6

The modeled monthly δ^{18}O values are rather close to obtained δ^{18}O, except at the lowest sampling point. The isotopic composition of precipitation (Figure 2, Table 1) also shows a lack of altitude effect (decrease in δ^{18}O with increasing altitude) in July 2023. Since the altitude effect was absent or weakly expressed in the precipitation, differences in the isotopic composition of precipitation at different altitudinal levels can be ignored in the process of hydrograph separations during summer 2023.

3.2. Isotopic Composition of Ice and Snow

Ice samples were taken from the ablation zone of the surface of the Bolshaya Taldura glacier at relatively regular intervals. This technique has been used before and has proven itself fit for determining the average isotopic composition of ice [31]. (Seasonal snow was collected from two snow pits in snow fields on the surface of the glacier tongue. In total, 45 ice and 17 snow samples were collected.) The sampling points and the isotopic composition of the ice and snow are shown in Figure 3.

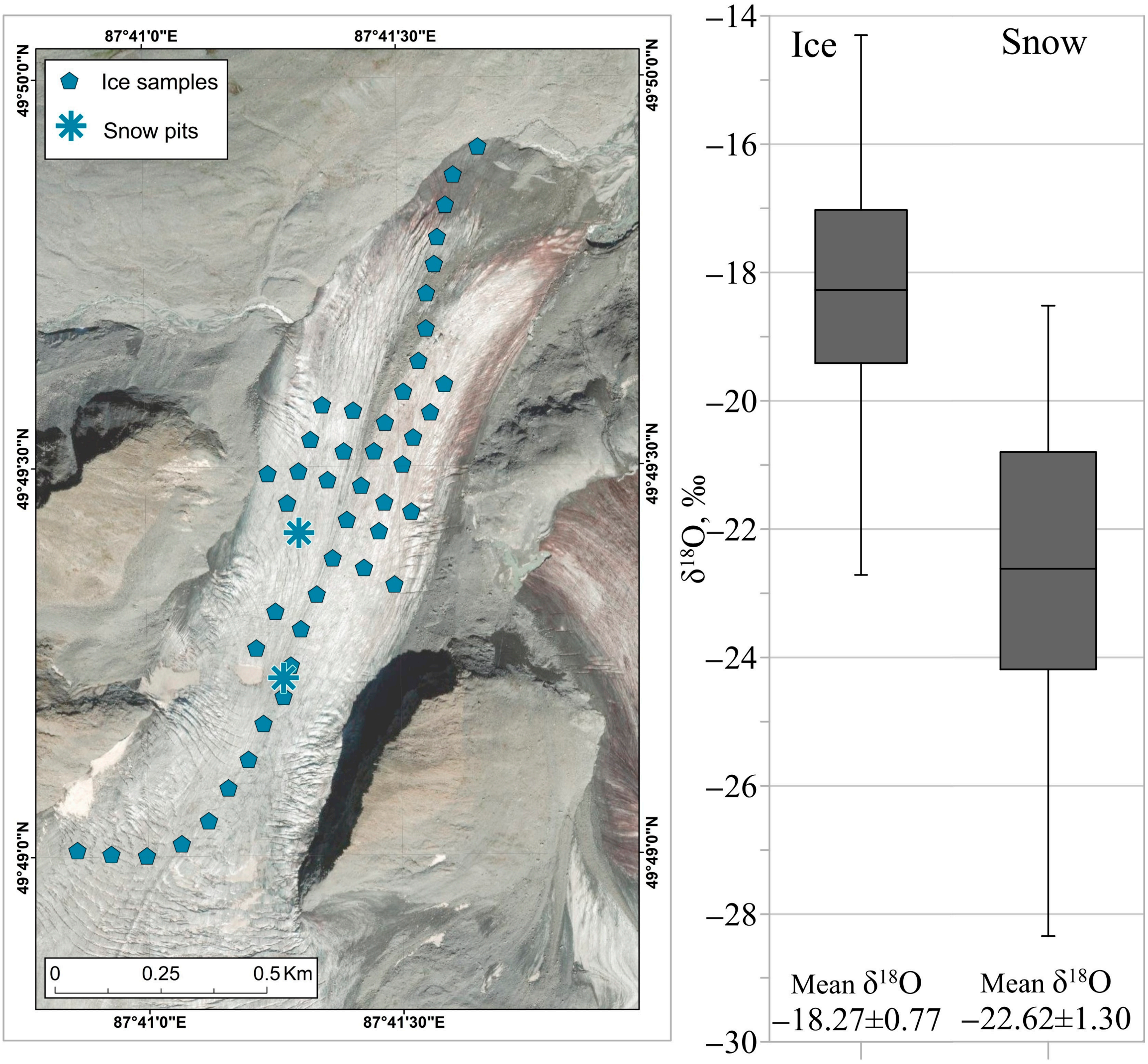

Figure 3. Sampling points on the surface of the Bolshaya Taldura glacier and $\delta^{18}O$ box plots for the glacier ice and snow.

The mean and range of $\delta^{18}O$ in glacier ice indicate the formation of ice from precipitation of the transitional seasons (autumn–spring). In the seasonal snow on the glacier surface, lower values of $\delta^{18}O$ are presented, so we can indicate this snow as winter snow from 2022–2023. The meteoric lines in the ice and snow are close to each other and close to the GMWL: $\delta^2H = 7.82 \times \delta^{18}O + 13.29$ in ice and $\delta^2H = 7.78 \times \delta^{18}O + 9.38$ in snow. These meteoric lines are almost very close to the meteoric line ($\delta^2H = 7.8 \times \delta^{18}O + 7.7$) obtained from 524 samples of firn core on the Belukha plateau in 2002 [8]. A summary of the ice and snow characteristics is shown in Table 2.

Table 2. Characteristics of the ice and snow from Bolshaya Taldura glacier.

Type	Number of Samples	Range of $\delta^{18}O$, ‰	Mean $\delta^{18}O$, ‰	TDS, ppm	Meteoric Water Line
Ice	45	−26.67–−12.31	−18.27 ± 0.77	2.5 ± 0.8	$\delta^2H = 7.82 \times \delta^{18}O + 13.29$
Snow	17	−18.52–−28.34	−22.62 ± 1.30	8.4 ± 5.4	$\delta^2H = 7.78 \times \delta^{18}O + 9.38$

The ice is characterized by very low values of total dissolved solids (TDS). In the snow, the mean TDS is 8.4 ppm; this value is also quite low. The high confidence interval is explained by the smaller number of snow samples taken.

3.3. Isotopic Composition of Water

For every observation day at each gauging station, the mean $\delta^{18}O$ was calculated. Figure 4 shows that the variability in $\delta^{18}O$ at the lower hydrological post is less than that at the upper one, while the courses of the $\delta^{18}O$ values at the two gauges for the total period coincide. Precipitation at the lower post practically has no effect on the isotopic composition of the water.

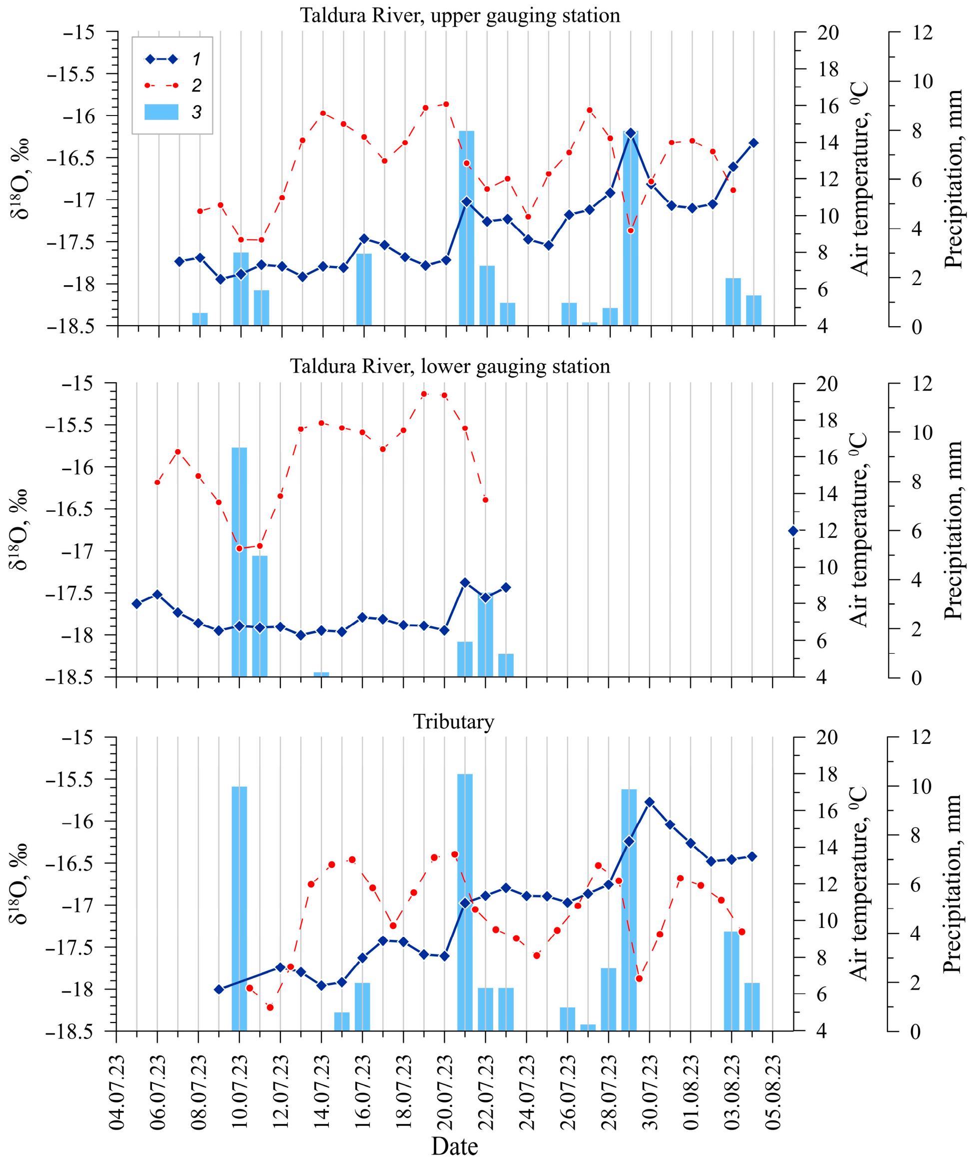

Figure 4. Changes in $\delta^{18}O$ and meteorological parameters at gauging stations. 1—$\delta^{18}O$; 2—temperature; 3—precipitation.

The increase in $\delta^{18}O$ at each gauge is associated with precipitation. At the same time, the highest value of $\delta^{18}O$ at the upper gauging station was recorded on 29.07, when a large amount of precipitation occurred at the period of low air temperature and, consequently, minimal melting. In general, there was a tendency for an increase in $\delta^{18}O$ at the upper gauging station after 21.06.

At the lower gauging station, the situation is uncommon: the $\delta^{18}O$ values in general are lower than at the upper one, which indicates a greater fraction of glacier meltwater to the runoff, despite the distance of 34 km from the edge of the Bolshaya Taldura glacier. But a separate sample taken at the lower post on 06.08 showed that there was a tendency for

$\delta^{18}O$ to increase, as well as at the upper post. There is also minimal variability in $\delta^{18}O$ at the lower gauge during the observation period.

At the gauging station on the tributary, the range of $\delta^{18}O$ is greater and the mean $\delta^{18}O$ is higher, which indicates a greater influence of precipitation on the runoff in the small tributary. As the other two gauges, there is trend of an increase in $\delta^{18}O$ over time and the peaks of $\delta^{18}O$ after precipitation events are pronounced.

Samples were also taken from different tributaries of both glacial and non-glacial origin. The water characteristics obtained from the gauges and tributaries are shown in Table 3.

Table 3. Average characteristics of water samples by group.

Type of the Samples	Mean Discharge, m^3/s	Mean $\delta^{18}O$, ‰	Mean TDS, ppm
Gauge 1, lower Taldura	25.0	−17.77	41.9
Gauge 2, upper Taldura	10.95	−17.30	3.3
Gauge 3, tributary	1.08	−17.05	7.8
Glacier-originated tributaries	-	−17.58	18.4
Non-glacier-originated tributaries	-	−15.77	36.3

The obtained mean value and the range of $\delta^{18}O$ (from −18.79 to −16.57‰) of water from glacier originated tributaries are very close to the isotopic composition of water at the gauging stations on the Taldura River. It can be suggested that these values are typical for the glacier rivers of the ridge in the middle of the ablation season.

The mean $\delta^{18}O$ value in the streams of non-glacial origin is −15.77‰ (from −17.11 to −14.55‰). The relatively low isotopic composition indicates the contribution of snowmelt water to their feeding.

In the upper reach of the Taldura River (gauge 2), the TDS changes slightly during the observation period (within 2–4 ppm). At the lower reach of the Taldura river (gauge 1), the TDS was 10 times higher because of enrichment from the dissolved mineral compounds. On the right tributary of the Taldura River, the TDS remains almost unchanged throughout the observation period (7–8 ppm).

The TDS in the glacier-originated tributaries is lower than the mineralization of non-glacial originated tributaries but higher than the water conductivity at gauges 2 and 3, because of the filtration through moraine.

3.4. Isotopic Separation

The isotopic composition of the water on the gauges of the Taldura River reflects a mixture of water from different sources (Figure 5). The positions of the gauges on this diagram show the dominance of meltwater in river feeding.

According to the isotope balance equation, Equation (3), a two-component separation of hydrographs was performed. Several assumptions have been made to facilitate the separation. Only glacier meltwater and precipitation were considered components because it is possible to separate only two components using only $\delta^{18}O$ as a tracer. It was also assumed that there is no separate groundwater reservoir in the studied basin, which differs in isotopic composition from summer precipitation and meltwater. This fact is confirmed by the absence of significant springs forming large tributaries in the Taldura river basin.

The average value $\delta^{18}O$ of the glacial ice of the Bolshaya Taldura glacier was taken as the isotopic composition of meltwater. Precipitation was considered the second component, since the trends in the isotopic composition of water at all gauging stations showed that precipitation affects changes in the isotopic composition of river water. The isotopic composition of precipitation was taken as the weighted-average value of $\delta^{18}O$ for the day before sampling, and the daily course of the isotopic composition of water showed that the run-up time did not exceed 24 h. If no precipitation occurred, the separation was performed using the isotopic composition of the last precipitation event. The results of isotopic separation at the Taldura River gauging stations are shown in Figure 6.

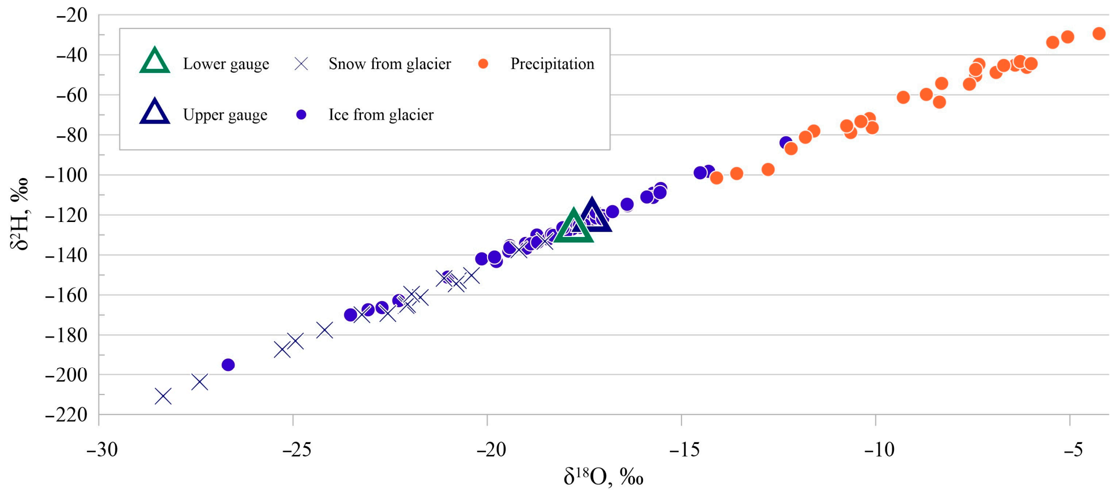

Figure 5. $\delta^{18}O$–δ^2H diagram for different groups of the samples.

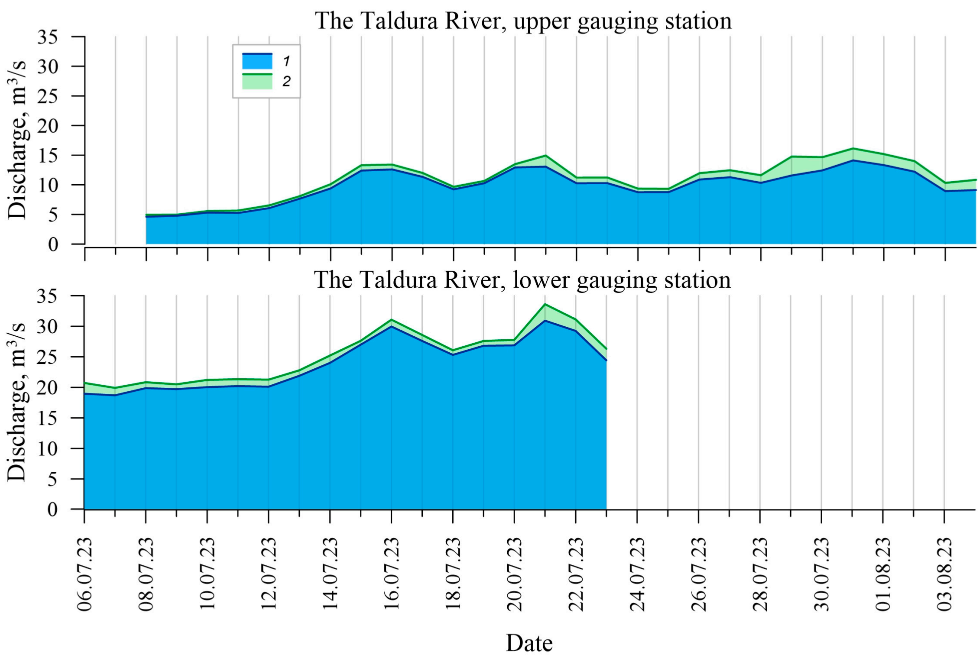

Figure 6. Separated hydrographs of the Taldura River: 1—meltwater of glaciers; 2—precipitation.

At the upper hydrological gauging station, the fraction of precipitation in runoff varied from 4 to 22% and averaged 9%. The average daily discharge formed from atmospheric precipitation varied from 0.18 to 3.19 m^3/s. The maximum fraction of precipitation was observed on 29–30 July after a large amount of precipitation, with a decrease in temperature and, as a result of the low temperature, a decrease in melting.

At the lower gauging station, over a shorter observation period (until 23.07), the fraction of precipitation varied from 2 to 9%, with an average precipitation fraction of 5%. The average daily discharge formed from precipitation varied from 0.64 to 2.70 m^3/s. During this period the discharges formed by precipitation in the upper gauging station were 0.18–1.88 m^3/s. This fact may indicate that the isotopic separation results are correct. The maximum precipitation fraction in the runoff was observed on 21–23 July after precipitation in the upper part of the basin. It was also found that on 06.08 (based on an additional sample, not included in Figure 5), the fraction of precipitation increased to 17%.

The tributary (gauge 3) is characterized by an order of magnitude lower discharge. It was found that the fraction of precipitation varied from 5 to 32% (on average 15%), which is greater than on the Taldura River, but it is still mostly insignificant.

4. Discussion

First, it is necessary to sum up the obtained data on the isotopic composition of precipitation. The altitude effect of changes in the isotopic composition of precipitation is not pronounced: a decrease in the values of $\delta^{18}O$ with an increase in altitude is not observed. The absence of an altitude effect can be explained by precipitation from a single condensation level when the air mass does not rise up along the valley or slopes. The reverse altitude effect (minimal $\delta^{18}O$ at the lower gauge) may be associated with various sources of moisture and the turbulent mixing of air masses on orographic barriers [32].

A comparison of precipitation $\delta^{18}O$ with OIPC data showed a close agreement. Therefore, the data from this online calculator may be used for further large-scale isotope hydrological studies.

The isotopic composition of the ice from Bolshaya Taldura can be used in further isotopic separation research in the upper Chuya basin as the isotopic composition of meltwater. The obtained mean $\delta^{18}O$ value is close to the isotopic composition of ice in the Eastern Altai [14]. In the Western Altai, glacier ice must be enriched with stable isotopes according to the greater fraction of summer snow in glacier feeding. This is confirmed by ice drilling results on the Belukha plateau [8].

Changes in the water $\delta^{18}O$ at each gauge reflect the influence of precipitation and changes in melting intensity. The low variability in $\delta^{18}O$ in the lower gauge is explained by averaging the isotopic characteristics of all the water in the basins studied. Small tributaries are more affected by precipitation and temperature changes. This is reflected in the greater variability in water $\delta^{18}O$.

It is interesting that the fraction of glacier feeding in the Taldura River increases with distance from the Bolshaya Taldura glacier. The decrease in the precipitation fraction in the Taldura River from the upper part of the basin to the lower part is explained by the influence of glacier-originated tributaries with a natural decrease in precipitation in the lower part of the basin. The waters of the tributaries, as mentioned above, have an average value of $\delta^{18}O$ −17.61‰. Some of them are characterized by the dominance of glacier meltwater with low $\delta^{18}O$ values in water, e.g., the mean $\delta^{18}O$ from three samples in the Dzelo River (see Figure 1) is −18.17 ‰. In addition, the amount of precipitation in the lower part of the catchment area is naturally decreasing. Thus, glacial feeding prevails completely in the runoff in the Taldura River throughout its entire length and in the runoff in its main tributaries.

Judging by the low values of $\delta^{18}O$ at the start of the observation period at all gauging stations (Figure 4), we can suggest that snow meltwater, which is characterized by the lowest $\delta^{18}O$ (Table 2), contributed to the feeding of rivers. The hydrograph can be divided into three components (glacier meltwater, snow meltwater and precipitation) using two tracers. TDS is usually used as the second one, but in this case the values of the TDS of the ice, snow and precipitation were too close to each other. It is also possible to perform three-component separation using excess deuterium [1]. But for a correct three-component separation, we need more data on the isotopic composition of snow from the glaciers and snowfields over the entire catchment area. In any case, the low values of $\delta^{18}O$ in the lower reaches of the Taldura River can also be explained by an increase in the fraction of snow meltwater.

It is also interesting to investigate the interannual variability in the isotopic composition. Some samples were taken from the Taldura River a year before this research, in 2022. In 2022 and 2023, sampling was carried out in approximately one part of the ablation season (mainly in July), while various meteorological conditions were observed, which makes it possible to assess the variability in the contribution of glacier runoff to the feeding of the

Taldura River. A comparison of isotopic characteristics and meteorological conditions for the example of the upper gauging station is shown in Table 4.

Table 4. Comparison of data from 2022 and 2023 for the upper gauging station at the Taldura River.

Year	2022	2023
Observation period	11.07–29.07	11.07–29.07
Range of $\delta^{18}O$ in Taldura River, ‰	−15.05–−16.92	−16.06–−18.04‰
Mean $\delta^{18}O$, ‰ (upper gauge)	−16.22	−17.30
Mean T, °C (upper gauge)	+9.1	+12.7
Precipitation, mm	38	33

In 2022, the colder conditions with more precipitation, as a result of which the fraction of glacier runoff in the Taldura River's feeding was lower, were reflected in the isotopic composition. At the same time, for the precipitation in the Taldura River, the fraction in 2022 generally did not exceed 20%. Thus, even under different conditions in the middle of the ablation season, glacier meltwater completely prevails in Taldura River feeding.

5. Conclusions

Based on the results of a complex of field work and laboratory measurements, it was determined that glacier feeding completely prevails throughout the Taldura River in the middle of the ablation season. At the same time, there is even a slight increase in the fraction of glacier meltwater in the lower part of the basin, far from the Bolshaya Taldura glacier. The meltwater fraction at the mouth of the Taldura River can reach 95%. Near the source of the Taldura River, the meltwater fraction in general is around 80–95%. The second most important source of water is summer precipitation, but its contribution, depending on the conditions, usually does not exceed 10–20%. Thus, further degradation of the South-Chuya ridge's glaciation will inevitably affect the runoff in the Taldura River and the water balance of the upper Chuya basin as a whole. Now, the role of glacier runoff in the Taldura River is very high, but with further retreat of the glaciers, in addition to a reduction in their area, the intensity of their melting will decrease, since the edges of the glaciers will be higher. Consequently, in the near future, glacier runoff may even increase, but with continued degradation of glaciation, it will inevitably decrease, which will lead to a significant decrease in runoff in the Taldura River.

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Data Availability Statement: Isotopic data used for hydrographs separation is available at https://disk.yandex.ru/i/VvaJvO-nlLRbuw.

Conflicts of Interest: The authors declare no conflict of interest.

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