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Catchment-specific factors influencing isotopic variability of glacier melt and snowpack in the Himalayas

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This study investigates the impact of catchment-specific environmental factors, such as aspect, albedo, and temperature, on isotopic variability in glacier melt and snowpack samples across three Himalayan catchments: Lidder, Sindh, and Rambiara. The findings reveal significant correlations between isotopic composition and environmental factors. Key predictors, particularly aspect and temperature, were identified, with R^2 values indicating moderate to strong correlations. Aspect emerged as a primary factor influencing isotopic variability, especially in the Rambiara snowpack, where solar radiation exposure significantly shaped snow characteristics. In the Sindh catchment, the day of sampling (DOS) and temperature played crucial roles in isotopic variability, highlighting the importance of temporal and thermal factors. Albedo, reflecting surface radiation characteristics, was also found to influence isotopic composition in Sindh snow samples, likely affecting melt rates and snowpack stability. Altitude exhibited varying impacts across sample types and slopes. On the northern slopes of the Lidder catchment, glacier melt showed isotopic depletion with increasing elevation, typical of alpine glacial processes. Conversely, snow and snowpack samples on northern slopes exhibited moderate isotopic enrichment with altitude, likely influenced by wind redistribution and sublimation. In contrast, southern slopes showed minimal altitude influence on glacier melt and snow isotopic composition, with snowpacks at higher elevations showing moderate isotopic enrichment due to sublimation and partial melt processes. These findings underscore the complex interplay of environmental factors in shaping isotopic variability, emphasizing the need for high-resolution, catchment-specific studies. Future research should explore microclimatic conditions, wind redistribution, and snow metamorphism, as well as continuous monitoring and modeling efforts to enhance the understanding of isotopic trends and their implications for water resources in the Himalayan region.

KEYWORDS

snow dynamics, isotopic lapse rates, stable isotopes, glacier melt, altitude variation, Himalayas

1 Introduction

Stable isotopes of oxygen ($\delta^{18}O$) and hydrogen (δ^2H) are invaluable tools in hydrological research (Klaus and McDonnell, 2013), enabling the tracking of water movement and the analysis of climatic processes across diverse environments (Penna et al., 2017; Dar et al., 2024). Due to their conservative behavior within the hydrological cycle, these isotopes are invaluable for understanding the origins, transformations, and transport of water through various systems (Gat, 1996; Fekete et al., 2006). In particular, the investigation of isotopic variations in mountainous areas of isotopic variations in mountainous areas has proven essential for understanding the hydrological pathways of meltwater (Pant et al., 2021; Dar et al., 2024), snow accumulation dynamics (Carroll et al., 2022), and the governing processes of snowmelt. These factors are vital for predicting water availability in glacier-fed catchments (Zuecco et al., 2019).

Stable water isotopes are effective tools for tracing water flow paths and estimating travel times in hydrological systems (Kirchner et al., 2010; Birkel and Soulsby, 2015a). Precipitation in solid form typically shows depletion in heavy water isotopes ($\delta^{18}O$ and $\delta^{2}H$) relative to the mean annual signature due to lower temperatures during vapor condensation (Moser and Stichler, 1970). Consequently, the accumulated snowpack and subsequent snowmelt runoff exhibit isotopic depletion compared to the broader hydrological system. This depletion creates a detectable hydrological signal at freshet, useful for estimating the contribution of snowmelt to groundwater recharge (Earman et al., 2006; Jasechko, 2019), understanding runoff generation processes (Carey and Quinton, 2004; Laudon et al., 2004), and performing hydrograph separations to distinguish between older and newer water in streams (Sklash and Farvolden, 1979; Rodhe, 1981; Laudon et al., 2002).

Isotopic lapse rates (ILRs), which describe the change in isotopic composition with altitude, are vital for interpreting how elevation affects the isotopic signatures of meteoric waters. ILRs provide a framework for understanding isotopic data from different snow reservoirs, which can vary widely across mountain ranges and climatic settings. The isotopic profiles of snow, snowpacks, and glacier meltwater are vital for assessing water resource availability and offering insights into paleo-environmental conditions (Hren et al., 2009; Dietermann and Weiler, 2013). Unlike liquid precipitation, which exchanges isotopes with atmospheric humidity as it falls, snow retains the isotopic content formed during its condensation (Gat, 1996). Although the initial isotopic composition of snowfall contributes to the overall snowpack signal, factors such as mass transport through wind drift, avalanches, and fractionation due to equilibrium and kinetic processes alter the isotopic content of snow water. During periods without precipitation, sublimation removes snow layer by layer, causing fractionation influenced by temperature and vapor pressure gradients within the snowpack and between the snowpack and the atmosphere (Dar et al., 2024). Contrary to the expectation that sublimation of individual snow crystals would prevent isotopic change, heavy isotopes often become enriched in the upper snow layers due to water vapor diffusion and partial melting, leading to evaporation, meltwater percolation (Gat, 1996; Stichler et al., 2001), and kinetic fractionation (Gustafson et al., 2010; Biederman et al., 2014).

The altitude effect on stable water isotopes in precipitation has been well-documented since the pioneering work of Dansgaard (1964). Moser and Stichler (1970) demonstrated that the orographic uplift of air masses and the corresponding decrease in condensation temperature cause the depletion of heavy isotopes with altitude, an effect also observable in fresh snow. In the Sierra Nevada, Friedman and Smith (1970) reported a $\delta^{18}O$ depletion of −0.25 to −1.25‰ per 100 m. Niewodniczański et al. (1981) examined the altitudinal gradient of $\delta^{18}O$ across various mountain regions, including the Andes, Hindu Kush, and the Himalayas, finding an elevation gradient of −0.6 to −1.0‰ per 100 m. However, their data showed considerable variability, suggesting that the gradient was not strictly linear. This variability was attributed to factors such as wind drift, melting processes, and local topographic and climatic conditions. Moran et al. (2007) also found significant variation in $\delta^{18}O$ gradients in the Canadian Rockies, highlighting the influence of local meteorological conditions on the isotopic profile of snow at various altitudes.

While fresh snow shows clear isotopic gradients, the isotopic characteristics of entire snowpacks are more complex. Snowpacks are influenced by processes such as sublimation, evaporation, snow crystal metamorphism, and meltwater percolation, which can introduce additional fractionation effects (Moser and Stichler, 1970; Judy et al., 1970; Raben and Theakstone, 1994; Aizen et al., 1996; Stichler et al., 2001; Sinclair and Marshall, 2008; Sokratov and Golubev, 2009). These factors can modify the isotopic altitude effect observed in fresh snow, leading to inverse gradients, as reported by Moser and Stichler (1970) at the Kitzsteinhorn in Austria. Other studies (Raben and Theakstone, 1994; Gurney and Lawrence, 2004; König et al., 2008) found no significant correlation between the isotopic signature of entire snowpacks and elevation. These discrepancies may be explained by limited elevation ranges and differences in snow accumulation processes. Understanding the evolution of snowpack and snowmelt isotope dynamics is critical for implementing tracer-aided modeling approaches in catchments affected by these processes (Lyon et al., 2010; Peralta-Tapia et al., 2016), which are increasingly used to assess mixing, storage dynamics, and travel times in snow-fed catchments (Birkel and Soulsby, 2015b; Berman et al., 2009).

In mountainous regions such as the Himalayas, snowpacks and glaciers are crucial freshwater sources (Immerzeel et al., 2010; Lutz et al., 2014). The elevation effect on the isotopic composition of precipitation and its subsequent impacts on snow and glaciers highlights the importance of understanding the isotopic variability in these systems (Voss et al., 2018; Carroll et al., 2022). Elevation influences the isotopic profile of precipitation due to temperature-dependent fractionation during condensation (Moser and Stichler, 1970; Gonfiantini et al., 2001). Research indicates fresh snow becomes more depleted with increasing altitude, due to lower condensation temperatures (Niewodniczański et al., 1981; Moran et al., 2007). However, post-depositional processes such as sublimation, metamorphism, and meltwater percolation can complicate the isotopic profiles, introducing additional fractionation that modifies the original snow isotopic signatures (Gat, 1996; Stichler et al., 2001).

2 Study region

This study was conducted across three major catchments—Lidder, Sindh, and Rambiara—located in the western Himalayas. These catchments represent a wide range of altitudes, climatic conditions, and hydrological regimes, from temperate to alpine environments. These regions play a crucial role in downstream water systems (Dar et al., 2024). The selected catchments were chosen for their diverse topographical characteristics, including north- and south-facing slopes, to assess the influence of aspect and elevation on snowpack and meltwater isotopic composition. The geographical locations of the catchments are presented in Figure 1. Sample data for snow, snowpack, and glacier melt were

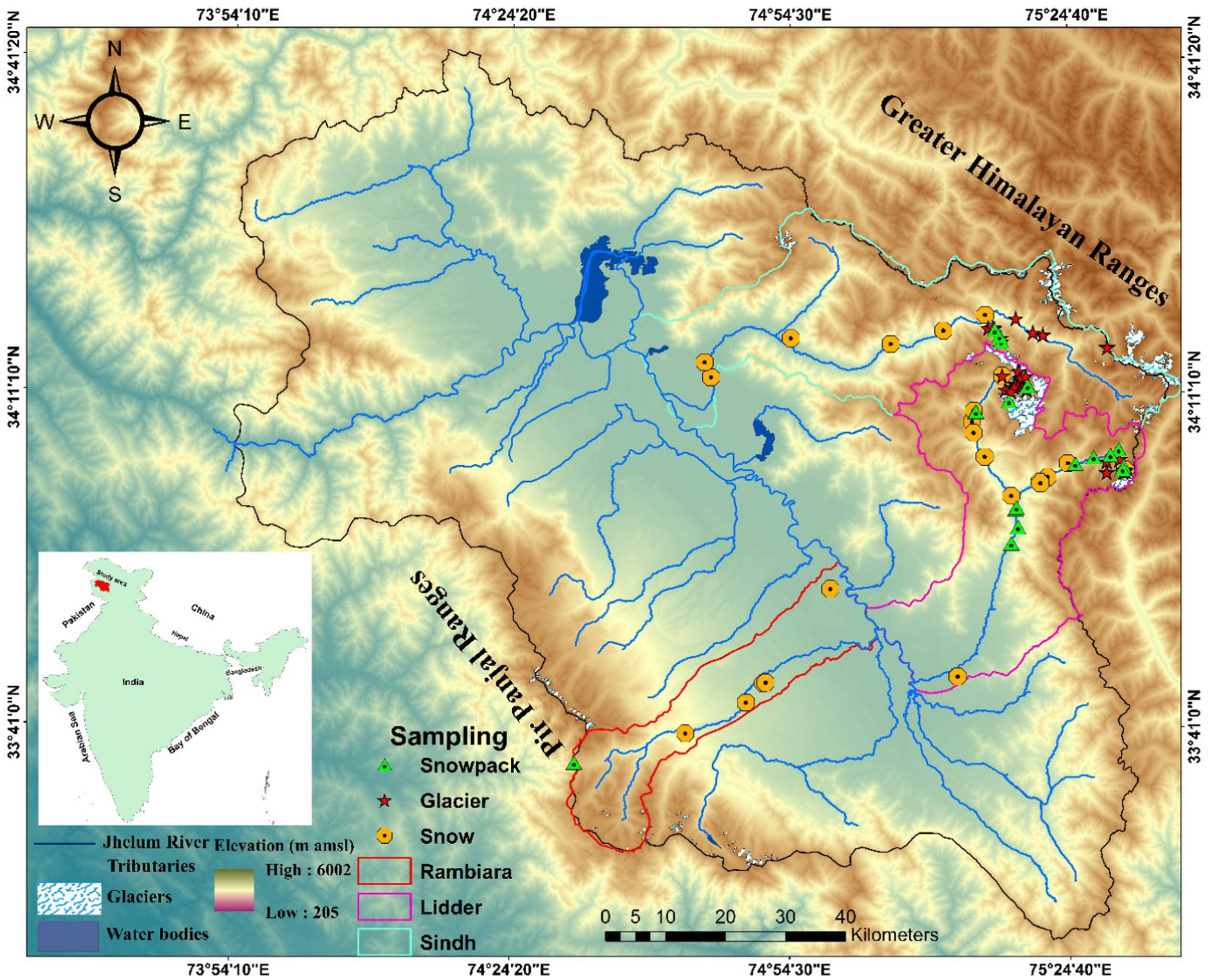

FIGURE 1
Geographical locations of the Lidder, Sindh, and Rambiara catchments in the western Himalayas, indicating sampling sites.

sourced from our previously published research (Dar et al., 2023, 2024).

3 Methodology

3.1 Sample collection

Sampling sites were distributed across a broad altitudinal gradient, ranging from 1,600 m to 4,000 m above sea level (asl), covering a variety of environmental settings (Figure 2). Each sampling site was categorized based on its elevation and slope aspect (north- or south-facing), enabling a detailed analysis of how these factors influence isotopic signatures in snow and meltwater.

Sampling was conducted during two key periods: the snow accumulation season (winter) and the melt season (spring to autumn). This sampling strategy was designed to capture temporal variations in isotopic composition related to snow deposition and melt dynamics, allowing for a comprehensive examination of the influence of seasonal changes on isotopic variability.

3.2 Sample analysis

The isotopic analysis of snow and glacier meltwater samples was conducted at the National Institute of Hydrology, Roorkee, India. Isotopic ratios of δ^2H and δ^{18}O were measured using two different mass spectrometry techniques: a Dual Inlet Isotope Ratio Mass Spectrometer (DI-IRMS, Isoprime) for δ^2H and a Continuous Flow Isotope Ratio Mass Spectrometer (CF-IRMS, Isoprime) for δ^{18}O. For δ^2H measurements, Pt-H_2 equilibration was employed, while δ^{18}O was measured using the CO_2 equilibration method, following standard protocols (Brenninkmeijer and Morrison, 1987; Epstein and Mayeda, 1953). A sample volume of 300 µL was used for each isotope analysis, with hook beads serving as a catalyst for δ^2H measurements. To ensure accuracy and precision, secondary internal standards were analyzed alongside the unknown samples, and a triple-point calibration procedure was implemented (Brenninkmeijer and Morrison, 1987). The reproducibility of isotopic measurements was ±0.07‰ for δ^{18}O and ±0.5‰ for δ^2H, which is within acceptable error margins for such analyses. Isotopic ratios were reported in δ notation (‰) relative to the Vienna Standard Mean Ocean Water (V-SMOW) in accordance with international standards (Gonfiantini, 1978).

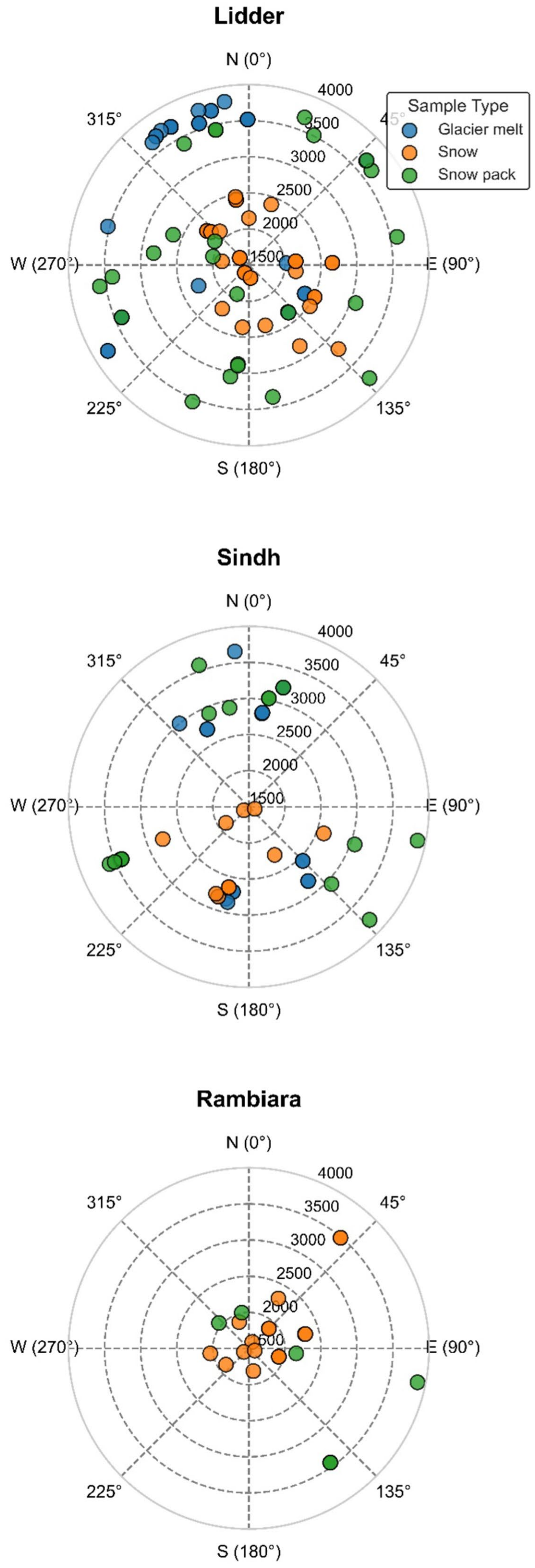

FIGURE 2
Elevation and aspect of every sample (Glacier melt, snow, and snow packs) collected from the three catchments of Lidder, Sindh, and Rambiara.

3.3 Statistical analysis of isotopic variations

This study employed a comprehensive statistical analysis to investigate the spatial, seasonal, and altitudinal variations in stable isotope compositions ($\delta^{18}O$ and $\delta^{2}H$) of snow, snowpacks, and glacier meltwater across the western Himalayas. Descriptive statistics were initially calculated for the isotopic data, categorized by sample type (fresh snow, snowpacks, and glacier melt) and elevation gradients. The primary focus was on determining the Isotopic Lapse Rate (ILR), which describes how isotopic composition changes with altitude. The Isotopic Lapse Rate (ILR) was estimated using Equation 1:

$$\text{ILR} = \left(\Delta\delta / \Delta Z\right) \quad (1)$$

where $\Delta\delta$ is the change in isotopic composition (‰) and ΔZ is the change in elevation (m). A multiple linear regression (MLR) analysis was then conducted, with isotopic compositions ($\delta^{2}H$) as response variables and a variety of environmental factors, including altitude, slope, snow depth, and temperature, as predictors. Stepwise backward elimination was used to refine the model, selecting significant predictors based on the Akaike Information Criterion (AIC). To assess the effects of wind drift and ablation, snow depth was included as a proxy variable. Additionally, environmental factors such as aspect were derived from a Digital Elevation Model (DEM), with aspect transformed using a cosine function to standardize values (Dietermann and Weiler, 2013). Temporal changes in isotopic enrichment during the ablation season were accounted for using the Day of Year (DOY). All statistical analyses were performed using Python software, providing robust insights into the isotopic dynamics of the study region. For multiple linear regression (MLR), Equation 2 was employed to examine the relationships between isotopic composition and environmental predictors:

$$\delta^{2}\text{H} = \beta 0 + \beta 1 \times \text{Temp} + \beta 2 \times \text{Aspect} + \beta 3 \times \text{Albedo} + \ldots + \beta n \times \text{Xn} \quad (2)$$

Where $\beta 0$ is the intercept, $\beta 1$ to βn are the coefficients, and Xn represents the environmental predictors such as temperature, aspect, and albedo. The model uses stepwise backward elimination to refine the selection of significant predictors based on the Akaike Information Criterion (AIC).

The coefficient of determination (R^2) was calculated using Equation 3 to assess how well the model explains the variance in isotopic composition:

$$R = 1 - \frac{\sum_{i=1}^{n}\left(\delta_{i}^{obs} - \hat{\delta}_{i}^{pred}\right)}{\sum_{i=1}^{n}\left(\delta_{i}^{obs} - \hat{\delta}_{i}^{obs}\right)} \quad (3)$$

Temporal variations in isotopic compositions were assessed using a two-way analysis of variance (ANOVA), examining the effects of seasonality and altitude, with post-hoc Tukey's honest significant difference (HSD) test identifying significant seasonal shifts in isotopic values. To further explore the factors affecting isotopic variations, principal component analysis (PCA) was applied, isolating key variables such as altitude, temperature, slope, and aspect, which influenced post-depositional processes such as sublimation and meltwater percolation. Pearson's correlation coefficient (r) was also calculated to assess relationships between isotopic compositions and environmental variables such as altitude, temperature, and precipitation.

4 Results

4.1 Influence of environmental factors on isotopic signatures

Several environmental variables significantly influence the isotopic composition of snow, snowpack, and glacier melt in the study catchments (Table 1). Temporal variables, particularly the DOS, show moderate correlations with the isotopic signatures. For instance, in the Sindh catchment, isotopic composition correlates moderately with DOS ($R^2 = 0.57$, $p = 0.02$), indicating some temporal influence during snow accumulation and melt periods (Dietermann and Weiler, 2013). The slope aspect emerged as an important control in specific scenarios. Notably, snowpack samples from the Rambiara catchment had a very high dependence on aspect ($R^2 \approx 0.99$, $p < 0.01$), indicating almost complete control by slope orientation. In contrast, aspect had a minimal influence on glacier melt isotopic signatures across all catchments (consistently low R^2 values). Albedo exhibited variable control over δ^2H values across sites (Table 1). In the Sindh catchment, the albedo was a significant predictor for glacier melt ($R^2 = 0.43$, $p = 0.01$) and snowpack samples ($R^2 = 0.36$, $p = 0.02$), suggesting that darker surfaces likely enhanced energy absorption and subsequent post-depositional modification. However, albedo showed negligible influence on snow isotopic composition in Sindh ($R^2 = 0.04$) and had limited explanatory power across all sample types in the Lidder and Rambiara catchments (Table 1).

The amount of annual average precipitation (AAP) did not show a consistent influence on isotopic composition across all catchments. A strong correlation was only observed in Rambiara snowpack samples ($R^2 = 0.65$, $p = 0.05$). However, this relationship was absent in Rambiara snow samples. Seasonal timing was another key factor: the day of the year (DOY) was a significant predictor for isotopic values in certain datasets, such as the Sindh glacier melt ($R^2 = 0.34$, $p = 0.02$) and the Rambiara snowpack ($R^2 \approx 0.91$).

Several topographic and geographic factors also influenced isotopic variability to varying degrees. In the Lidder catchment, mean air temperature (T_Avg) showed a weak but relatively stronger correlation with δ^2H in snow samples, explaining approximately 18% of the variance ($R^2 = 0.18$)—a higher contribution than other predictors in that subset.

Slope steepness exhibited a moderate effect on snowpack isotopes in the Sindh catchment ($R^2 = 0.42$, $p = 0.01$). By contrast, site elevation (altitude) alone was not a strong standalone predictor of isotopic composition in most samples, showing low and often insignificant correlations. Geographical location had a minor influence, as seen in the Lidder catchment, where latitude showed a small but significant correlation with snowpack δ^2H ($R^2 = 0.18$, $p = 0.03$). Terrain convexity or concavity (VC) was strongly correlated with snowpack isotopic values in certain areas (e.g., $R^2 = 0.97$, $p < 0.01$ for Rambiara snowpack), whereas VC had negligible impact on glacier melt isotopic composition.

4.2 Multiple linear regression analysis

Multiple linear regression (MLR) models were developed to quantify the combined effects of environmental variables on δ^2H in each catchment (Table 2). A stepwise backward elimination approach was used to refine each model by removing non-significant predictors. Partial residual plots (Figures 3–5) illustrate the influence of each selected predictor variable on δ^2H after accounting for the other variables in the model. In the Lidder catchment, the initial MLR model included 11 predictors (e.g., Albedo, T_Avg, VC, Aspect, AAP, Slope, Latitude, DOY, Altitude, Longitude, and Actual evapotranspiration (AET) and achieved $R^2 = 0.50$ (adjusted $R^2 = 0.07$). This model showed a moderate positive correlation ($R^2 = 0.50$), suggesting that 50% of the variance in δ^2H was explained by the variables. However, the adjusted R^2 of 0.07 and an F-statistic of 1.182 ($p = 0.38$) indicated that the model was not statistically significant, implying that the predictors collectively did not reliably explain δ^2H variations.

Subsequent models (Models 2 to 10) removed predictors based on statistical significance and multicollinearity. After removing VC, R^2 decreased slightly to 0.49, while the adjusted R^2 improved to 0.13. F-statistic increased to 1.37 ($p = 0.28$), though the model remained non-significant. After removing Albedo in Model 5, R^2 improved to 0.25, and F-statistic rose to 2.17 ($p = 0.09$), approaching significance. The final model, retaining only T_Avg and DOY, achieved $R^2 = 0.17$ and an F-statistic of 3.51 ($p = 0.04$). Although statistically significant, the model explains only 17.3% of the variance in δ^2H levels. The retention of T_Avg and DOY indicates the potential influence of seasonality and temperature on δ^2H, suggesting areas for further investigation.

In the Sindh catchment, the initial 11-predictor model showed a very high $R^2 = 0.96$ (adjusted $R^2 = 0.81$), though its significance was marginal ($F = 6.62$, $p = 0.07$), likely due to overfitting. Refinement of the Sindh model led to a final model with seven key predictors: Longitude, Latitude, Altitude, DOY, AAP, AET, and Slope. This final Sindh model was statistically significant, with $R^2 = 0.84$ (adjusted $R^2 = 0.84$, $F = 12.1$, $p = 0.002$). The retained predictors indicate that geographic location and climatic factors contributed substantially to δ^2H variation in the Sindh catchment. In the Rambiara catchment, the initial 12-predictor model yielded $R^2 = 0.72$ (adjusted $R^2 = 0.49$) and was statistically significant ($F = 3.11$, $p = 0.023$). Following the removal of less significant variables, the final Rambiara model included five predictors: DOY, Longitude, Aspect, Slope, and T_Avg. The final model had $R^2 = 0.65$ (adjusted $R^2 = 0.57$) with a highly significant overall fit ($F = 8.00$, $p < 0.001$). Thus, approximately two-thirds of the δ^2H variance in Rambiara was explained by a combination of seasonal timing and topographic/geographic factors. The Rambiara catchment's final model, with an R^2 of 0.65, effectively captures a significant portion of δ^2H variance. The key predictors—DOY, Longitude, Aspect, Slope, and T_Avg—highlight the combined influence of temporal factors (seasonality represented by DOY) and geographical characteristics on δ^2H dynamics. The statistical significance of these predictors underscores their essential roles in shaping hydrological and climatic interactions within the catchment.

4.3 Isotopic composition and meteoric water line

The δ^2H–δ^{18}O values of the samples cluster largely along the Global Meteoric Water Line (GMWL) in dual-isotope space (Figure 6). Most

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TABLE 1 Simple linear regression results showing R^2 and p-values for relationships between predictor variables and δ^2H values in glacier melt, snow, snowpack, and all sample types across the three Himalayan catchments (Lidder, Sindh, and Rambiara).

Predictor variables	Glacier melt			Snow			Snowpacks			All samples	All samples	All samples
	Lidder	Sindh	Rambiara	Lidder	Sindh	Rambiara	Lidder	Sindh	Rambiara	Lidder	Sindh	Rambiara
						R^2						
DOS	<0.001	–	–	0.20		–		0.02	0.57	0.12	0.07	0.05
Asp	0.02	0.07	–	0.01	0.06	0.04	<0.001	0.00	0.99	0.11	0.12	0.01
Albedo	0.02	0.43	–	0.04	0.04	<0.001	0.02	0.36	0.89	0.04	0.03	0.02
AAP	0.03	0.07	–	0.06	<0.001	0.05	0.05	<0.001	0.65	0.02	0.01	<0.001
VC	0.01	<0.001	–	<0.001	<0.001	0.20	0.01	0.14	0.97	0.00	<0.001	0.14
DOY	0.01	0.34	–	<0.001	0.01	0.18	0.13	0.00	0.91	0.02	0.02	0.28
T_Avg	<0.001	0.09	–	0.18	0.16	0.04	0.03	0.01	0.97	0.01	0.04	0.01
Slope	<0.001	0.09	–	0.05	0.03	0.23	0.01	0.42	0.80	0.20	0.11	0.08
Altitude	<0.001	0.17	–	<0.001	<0.001	0.01	0.06	0.07	**0.93**	0.02	0.06	0.07
AET	0.01	0.10	–	0.01	0.02	0.00	0.03	0.05	0.89	0.01	<0.001	0.06
Lat	0.08	0.35	–	<0.001	0.03	0.01	0.18	0.23	0.97	<0.001	0.02	<0.001
Long	0.01	0.06	–	<0.001	0.10	0.07	<0.001	0.01	0.92	<0.001	0.03	0.08
						p-value						
DOS	0.66	–	–	**<0.001**		–		0.63	0.02	0.01	**0.07**	0.28
Asp	0.03	0.35	–	0.45	0.30	0.39	0.96	0.98	**<0.001**	0.02	**0.02**	0.74
Albedo	0.34	**0.01**	–	0.21	0.43	0.96	0.48	**0.02**	0.01	0.65	0.24	0.49
AAP	0.27	0.34	–	0.13	0.90	0.34	0.27	0.96	**0.05**	0.14	0.44	0.60
VC	0.45	0.88	–	0.93	0.94	0.04	0.65	0.18	**<0.001**	0.73	0.87	**0.05**
DOY	0.49	**0.02**	–	0.81	0.71	**0.05**	**0.08**	0.88	**<0.001**	0.11	0.34	0.01
T_Avg	0.94	0.27	–	**0.00**	**0.09**	0.37	0.43	0.70	**<0.001**	0.40	0.15	0.61
Slope	0.70	0.29	–	0.15	0.47	0.03	0.64	**0.01**	**0.02**	**0.03**	0.47	0.15
Altitude	0.74	0.13	–	0.96	0.84	0.65	0.25	0.34	**<0.001**	0.13	**0.08**	0.19
AET	0.43	0.26	–	0.52	0.61	0.95	0.38	0.44	**0.01**	0.22	0.88	0.23
Lat	0.07	**0.02**	–	0.73	0.47	0.70	**0.03**	0.07	**<0.001**	0.97	0.33	0.86
Long	0.57	0.37	–	0.73	0.19	0.26	0.97	0.70	**<0.001**	0.88	0.23	0.16

Bold values indicate statistically significant correlations ($p < 0.05$). The p-values less than 0.001 are represented as "<0.001".

TABLE 2 Summary of stepwise multiple linear regression (MLR) models for Lidder, Sindh, and Rambiara catchments.

Catchment	Model	Key predictors	*R* value	R-squared	Adjusted R-squared	F statistic (ANOVA)	*p*-value (ANOVA)
Lidder	Model 1	Albedo, T_Avg, VC, Asp., AAP, Slope, Latitude, DOY, Altitude, Longitude, AET	0.707	0.5	0.077	1.182	0.382
	Model 2	Albedo, T_Avg, Asp., AAP, Slope, Latitude, DOY, Altitude, Longitude, AET	0.704	0.496	0.136	1.377	0.284
	Model 3	Albedo, T_Avg, Asp., AAP, Slope, Latitude, DOY, Altitude, Longitude	0.7	0.491	0.185	1.605	0.201
	Model 4	Albedo, T_Avg, Asp., AAP, Slope, Latitude, DOY, Longitude	0.698	0.488	0.232	1.904	0.13
	Model 5	T_Avg, Asp., AAP, Slope, Latitude, DOY, Longitude	0.688	0.473	0.256	2.177	0.09
	Model 6	T_Avg, Asp., AAP, Slope, DOY, Longitude	0.665	0.442	0.256	2.38	0.072
	Model 7	T_Avg, Asp., AAP, DOY, Longitude	0.633	0.4	0.243	2.537	0.064
	Model 8	T_Avg, Asp., AAP, DOY	0.615	0.378	0.253	3.036	0.042
	Model 9	T_Avg, AAP, DOY	0.572	0.327	0.231	3.4	0.037
	Model 10	T_Avg, DOY	0.492	0.242	0.173	3.512	0.047
Sindh	Model 1	Longitude, Latitude, Altitude, DOY, AAP, AET, Slope, VC, Asp., Albedo, DOS	0.98	0.96	0.816	6.626	0.073
	Model 2	Longitude, Latitude, Altitude, DOY, AAP, AET, Slope, VC, Asp., Albedo	0.979	0.958	0.853	9.153	0.023
	Model 3	Longitude, Latitude, Altitude, DOY, AAP, AET, Slope, VC, Asp	0.978	0.957	0.88	12.397	0.006
	Model 4	Longitude, Latitude, Altitude, DOY, AAP, AET, Slope, VC	0.975	0.951	0.886	14.589	0.002
	Model 5	Longitude, Latitude, Altitude, DOY, AAP, AET, Slope	0.961	0.924	0.848	12.167	0.002
Rambiara	Model 1	DOS, AAP, Albedo, Latitude, VC, DOY, Longitude, AET, Aspect, Slope, T_Avg, Altitude	0.853	0.728	0.494	3.119	0.023
	Model 2	DOS, Albedo, Latitude, VC, DOY, Longitude, AET, Aspect, Slope, T_Avg, Altitude	0.85	0.727	0.527	3.294	0.018
	Model 3	DOS, Albedo, Latitude, DOY, Longitude, AET, Aspect, Slope, T_Avg, Altitude	0.848	0.726	0.546	3.458	0.015
	Model 4	DOS, Albedo, Latitude, DOY, Longitude, Aspect, Slope, T_Avg, Altitude	0.847	0.724	0.565	3.69	0.012
	Model 5	DOS, Albedo, DOY, Longitude, Aspect, Slope, T_Avg, Altitude	0.844	0.711	0.591	3.831	0.01
	Model 6	DOS, DOY, Longitude, Aspect, Slope, T_Avg, Altitude	0.842	0.708	0.601	4.029	0.009
	Model 7	DOS, DOY, Longitude, Aspect, Slope, T_Avg	0.831	0.691	0.599	5.882	<0.001
	Model 8	Final Model (DOY, Longitude, Aspect, Slope, T_Avg)	0.81	0.656	0.574	8.003	<0.001

Each model iteration progressively removes predictors to evaluate their effect on R^2, adjusted R^2, and model significance (F-statistic and *p*-value). The final model in each catchment reflects an optimal balance between model complexity and explanatory strength, including only the most statistically relevant predictors. Bold values indicate statistically significant models ($p < 0.05$).

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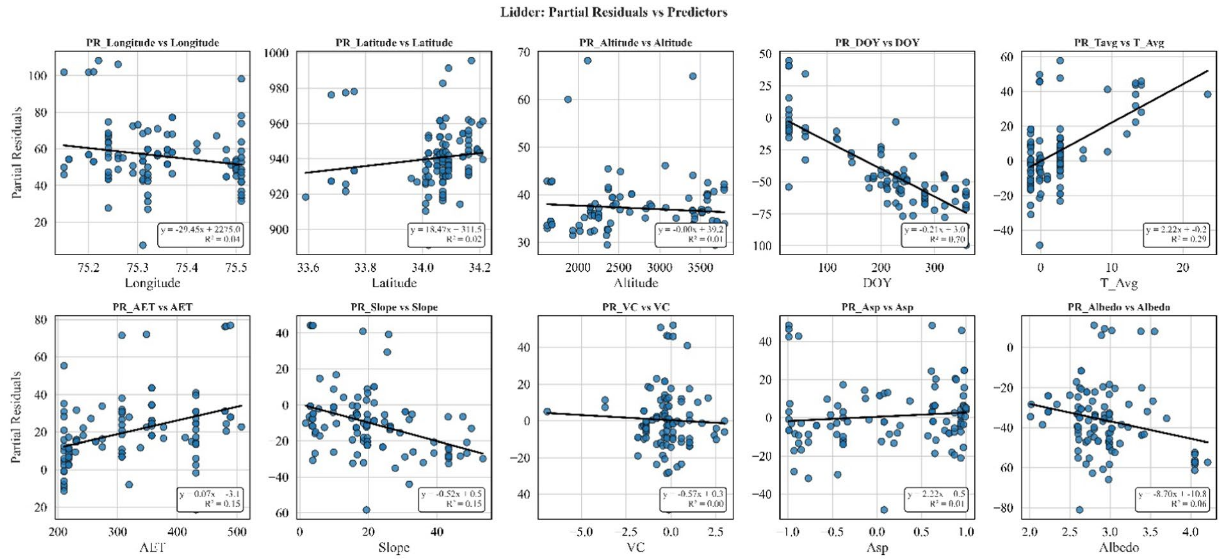

FIGURE 3
Partial residual plots for dominant predictors in the Lidder catchment, showing the isolated effect of each variable on δ^2H while accounting for the contributions of other explanatory variables in the multiple regression framework.

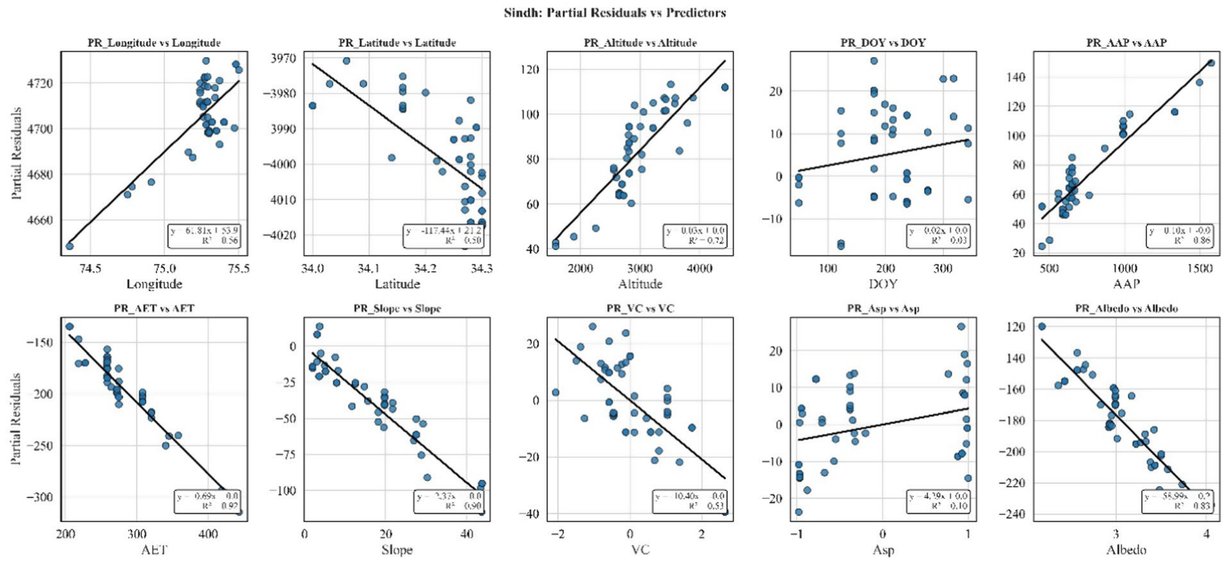

FIGURE 4
Partial residual plots for dominant predictors in the Sindh catchment, showing the isolated effect of each variable on δ^2H while accounting for the contributions of other explanatory variables in the multiple regression framework.

fresh snow and snowpack samples from all three catchments plot near the GMWL, with minimal deviation from that meteoric water reference. Snowpack samples collected during the melt season continue to align closely with the GMWL, although they exhibit a slightly broader scatter in isotopic values compared to winter snow samples. A few snow samples (particularly from the Sindh catchment) show minor positive deviations from the GMWL, but these are only limited outliers. Overall, no large departures from the meteoric water line (MWLs) were observed in the data, and there was no evidence of strong kinetic fractionation (e.g., from extensive evaporation or sublimation).

4.4 Isotopic lapse rates across slopes and catchments

Distinct altitude–isotope relationships (isotopic lapse rates, ILRs) were observed (Figure 7) for different sample types and slope orientations. In the Lidder catchment, the northern slope exhibited a clear altitudinal trend for glacier melt, with δ^2H decreasing at higher elevations (ILR ≈ −0.72‰ per 100 m; $R^2 = 0.36$). On the same northern slope, fresh snow showed a slight increase in δ^2H with altitude (ILR ≈ +0.45‰ per 100 m), whereas snowpack δ^2H varied

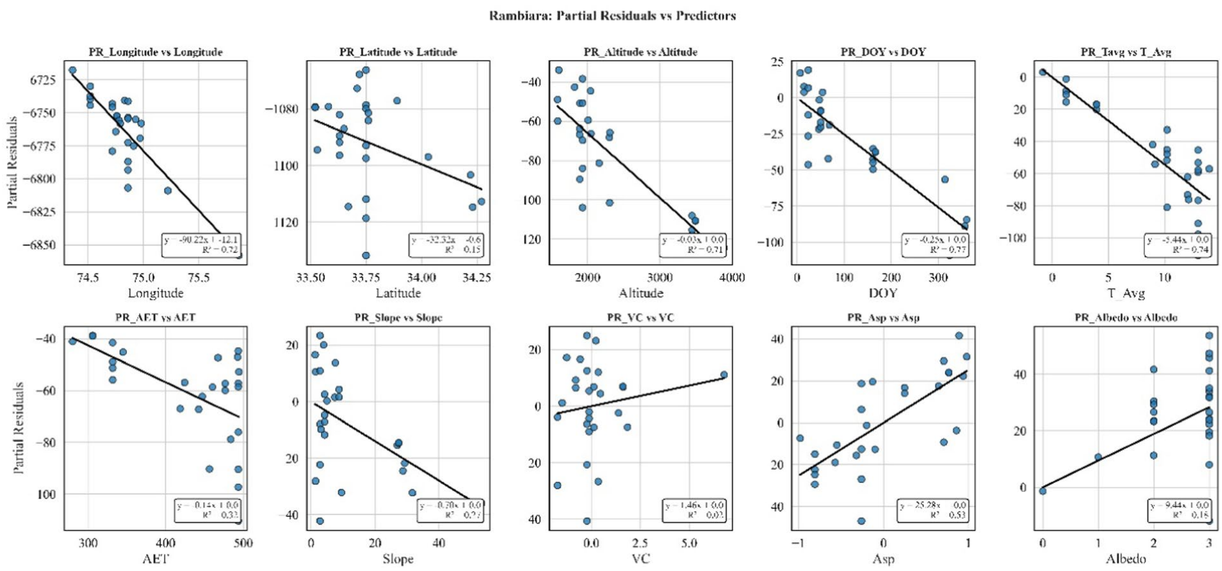

FIGURE 5
Partial residual plots for dominant predictors in the Rambiara catchment, showing the isolated effect of each variable on δ^2H while accounting for the contributions of other explanatory variables in the multiple regression framework.

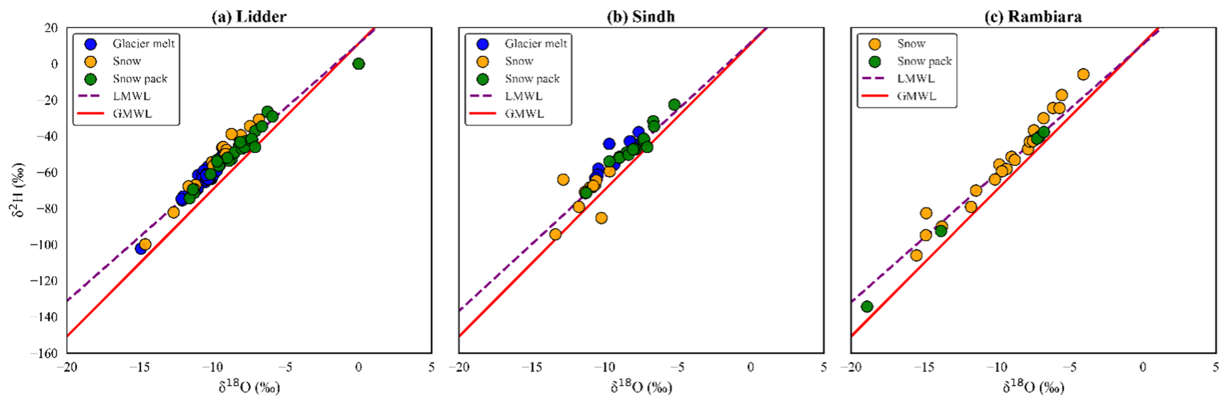

FIGURE 6
δ^2H versus $\delta^{18}O$ plots for snow, snowpack, and glacier melt samples from the **(a)** Lidder, **(b)** Sindh, and **(c)** Rambiara catchments. The Global Meteoric Water Line (GMWL; Craig, 1961) is shown as a red solid line. Local Meteoric Water Lines (LMWLs) are shown as purple dashed lines. The LMWLs for the Lidder, Sindh, and Vishow catchments were defined in our previous study (Dar et al., 2024). The Vishow catchment LMWL is used as a proxy for the Rambiara catchment due to its close geographic proximity and comparable climatic conditions. Glacier melt samples are included only for Lidder and Sindh due to data availability.

little with elevation (ILR ≈ −0.05‰ per 100 m, a near-zero slope; $R^2 = 0.32$). On the southern slopes of Lidder, both glacier melt and snow had essentially no change in δ^2H with altitude (very weak ILRs approximately 0‰ per 100 m, with $R^2 < 0.1$), while the snowpack exhibited a positive ILR of approximately +1.2‰ per 100 m ($R^2 = 0.52$), indicating heavier isotope enrichment at higher elevations in the snowpack.

In the Sindh catchment (southern slopes), the glacier melt showed a gentle positive isotopic lapse rate (ILR ≈ +0.06‰ per 100 m; $R^2 = 0.32$), implying slightly higher δ^2H at greater altitudes. The snow on the same slope had a negative ILR (≈ − 0.09‰ per 100 m; $R^2 = 0.63$), consistent with δ^2H depletion at higher altitudes. The snowpack in the Sindh catchment showed a strong positive altitude effect, with an ILR of approximately +0.03‰ per 100 m and a high correlation ($R^2 = 0.94$).

In the Rambiara catchment, data were available for the northern slope. The fresh snow ILR was negative (≈ −0.07‰ per 100 m; $R^2 = 0.37$), indicating moderately lower δ^2H values at higher elevations in that catchment. No strong altitude-related isotopic gradient was observed for other sample types in Rambiara.

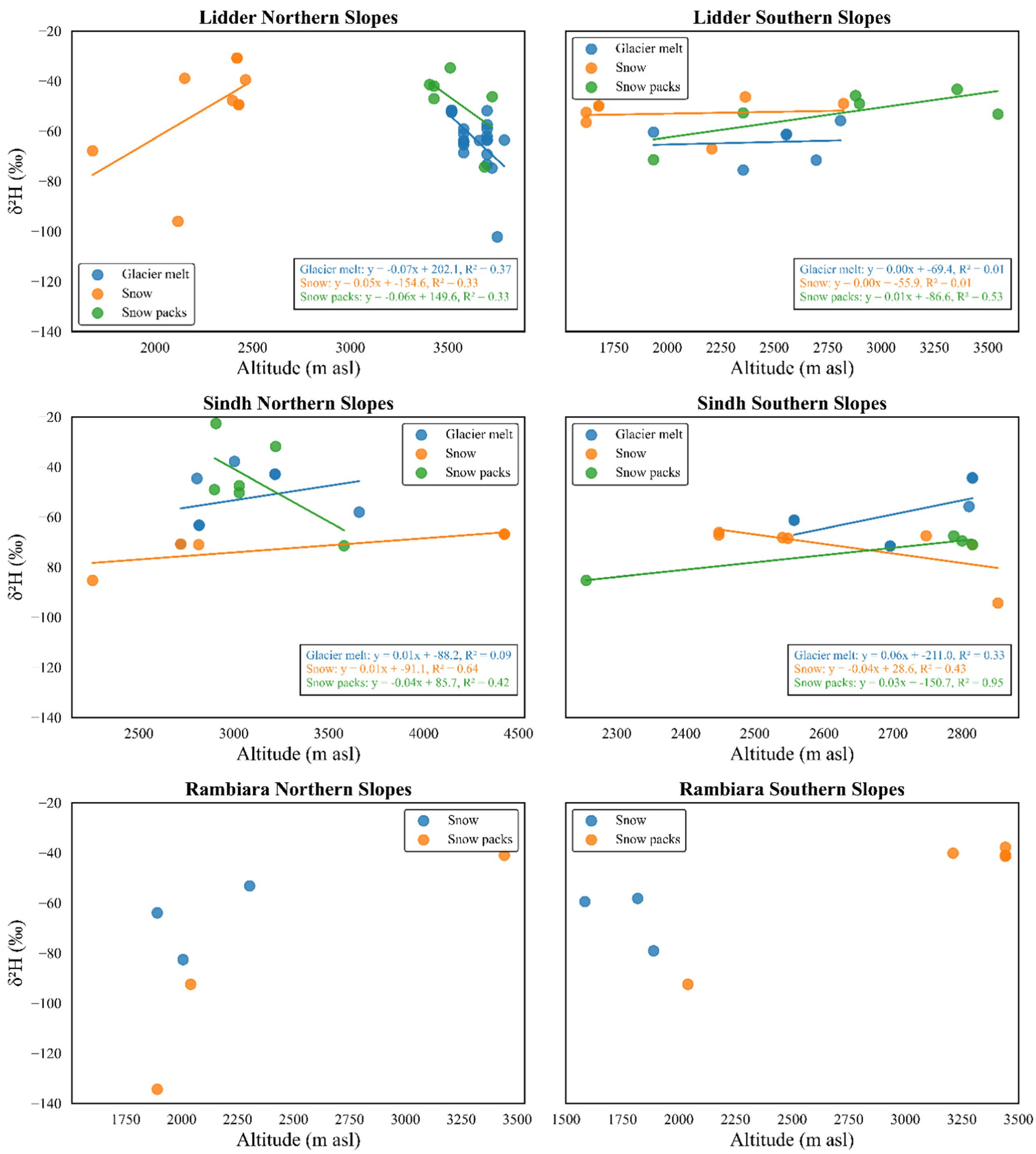

FIGURE 7
δ^2H vs. altitude for glacier melt, snow, and snowpack samples across northern and southern slopes of the Lidder, Sindh, and Rambiara catchments. Linear regression lines are shown where sufficient data exist. Regression lines for snow and snow pack samples of the Rambiara catchment were excluded due to limited data, as such fits are not statistically meaningful.

5 Discussion

5.1 Environmental controls on isotopic composition across catchments

Our results demonstrate that isotopic variability in snowfall and snowmelt is governed by a combination of catchment-specific environmental factors. Slope aspect proved to be a dominant control in some contexts: for example, the pronounced influence of aspect on the Rambiara snowpack ($R^2 \sim 0.99$) suggests that differential solar radiation exposure between north- and south-facing slopes leads to markedly different isotopic outcomes. South-facing slopes receive more intense sunlight, enhancing sublimation and evaporation, enriching the remaining snow in heavy isotopes relative to shaded slopes. This aligns with the understanding that solar exposure drives snowpack metamorphism and melt rates, significantly altering isotopic content. In contrast, we observed that aspect had little effect on glacier meltwater isotopic composition. This is plausible because glacier ice integrates over large areas and long-time scales, diluting micro-environmental differences. As observed by our previous work (Dar et al., 2024), the isotopic signal in glacier outflow tends to average out small-scale topographic effects that might otherwise influence snow on the ground.

Temporal factors, particularly those linked to seasonality, also played a critical role in shaping isotopic signatures. The moderate correlation of δ^2H with the day of sampling (DOS) in Sindh and the strong correlation with the day of the year (DOY) in the Rambiara snowpack indicate that seasonal progression (accumulation vs. melt season) exerts a strong influence on isotopic values. Such seasonal patterns have been documented in other alpine environments, where winter precipitation and spring melt impart distinct isotopic signatures over time (Dietermann and Weiler, 2013). In our study, samples collected later in the melt season generally showed evidence of isotopic enrichment, consistent with progressive fractionation as snowpack ablates. This seasonal effect is reflected in the inclusion of DOY as a significant predictor in the regression models for multiple catchments (e.g., Sindh and Rambiara). Dietermann and Weiler (2013) similarly found that the timing within the accumulation and melt season can influence isotopic ratios, likely due to the cumulative effects of melting and refreezing cycles.

Surface conditions and terrain features further modulate the isotopic composition. The influence of albedo in the Sindh catchment's snow samples suggests that darker surfaces (lower albedo) promote faster melting and evaporation, which in turn can cause isotopic enrichment of the residual snow. Areas with high albedo (bright, reflective snow or ice) would melt more slowly, potentially preserving a more depleted isotopic signature, whereas low-albedo areas absorb more solar radiation and experience greater fractionation of isotopes. Slope steepness was another factor: the moderate effect of slope angle on Sindh snowpack isotopes ($R^2 \sim 0.42$) implies that steeper slopes may lose snow more quickly via runoff and avalanching, leading to differences in isotopic content compared to gentler slopes. This observation is consistent with findings by Schmieder et al. (2016), who noted that steep terrain can result in reduced snow residence time and altered isotopic signals. Similarly, the strong correlation with terrain convexity (VC) in Rambiara's snowpack highlights the role of micro-topography. Concave, sheltered areas can accumulate and retain snow, allowing for layer-by-layer metamorphism and isotope retention, whereas convex, exposed areas tend to shed snow and promote sublimation (Dietermann and Weiler, 2013). Our data reflect this: the concavity index was a significant factor where snowpacks persisted but was unimportant for glacier melt since glaciers span broader topographic domains where microscale features average out.

The relative insignificance of altitude as a sole predictor in our correlation analysis underlines the complexity of these mountain systems. Although elevation strongly influences environmental conditions (temperature, precipitation form, etc.), its effect on snow and meltwater isotopes was often masked by the interplay of the other factors discussed above. For instance, in regions where wind redistribution or differential solar input is pronounced, two sites at different altitudes may end up with similar isotopic signatures despite the elevation difference. This finding reinforces the need for catchment-specific calibration of isotope–elevation relationships rather than relying on a universal altitudinal gradient. Each catchment exhibited a unique combination of dominant controls—for example, climatic inputs (precipitation amount and air temperature) were more important in the Sindh catchment, whereas local topographic factors (aspect and slope) were paramount in Rambiara. Therefore, any hydrological modeling or isotopic fingerprinting in these Himalayan basins should consider the distinct environmental controls present in each catchment. Developing high-resolution, site-specific models is essential for accurately interpreting isotopic data in such heterogeneous mountain terrain.

5.2 Altitudinal and seasonal effects on isotopic signatures

Atmospheric temperature gradients predict that precipitation becomes progressively depleted in heavy isotopes with elevation (Moser and Stichler, 1970; Niewodniczański et al., 1981). In line with this expectation, we observed the classical altitude effect in some instances: for example, glacier meltwater on the northern slope of the Lidder catchment showed δ^2H depletion with increasing altitude (ILR ≈ −0.72‰/100 m), and snow on the southern slope of the Sindh catchment similarly became lighter isotopically at higher elevations. These patterns arise from cooler temperatures and Rayleigh distillation during orographic uplift, which preferentially removes heavy isotopes from the vapor as it ascends and cools. However, our results also reveal notable deviations from the typical altitudinal depletion trend. In several cases, we found either minimal altitude dependence or an inverse relationship. For instance, on the northern slopes of Lidder, fresh snow samples exhibited a slight enrichment in heavy isotopes with altitude (positive ILR). This counterintuitive result suggests that post-depositional processes can modify the original altitude effect. One likely explanation is wind-driven redistribution of snow: winds can transport snow from lower to higher elevations, depositing relatively heavier (less depleted) snow at upper elevations, which would offset the normal altitude gradient file. Additionally, sublimation at higher altitudes can remove a portion of the lighter isotopes from the snowpack, leaving the remaining snow enriched in heavy isotopes; over time, this would lead to higher δ^2H at greater elevations, as observed in those Lidder and Rambiara snow samples. Conversely, on some sun-exposed slopes, we observed virtually no change in isotopic composition with altitude for snow and meltwater. Such homogenization can occur when frequent melting and refreezing cycles redistribute isotopic content through the snowpack, effectively erasing the altitude gradient. Schmieder et al. (2016) documented that percolation of meltwater and exchange with atmospheric moisture can diminish altitude-dependent isotope differences, which likely explains the weak altitudinal signals on the warm southern slopes of our study area.

Seasonal influences on isotopic composition were closely intertwined with altitude effects. As the winter snowpack transitions to spring and summer melt conditions, a suite of fractionation processes alters the isotope ratios (Penna et al., 2017; Pant et al., 2021; Dar et al., 2024). During the melt season, increased solar radiation and warmer temperatures drive sublimation and evaporation from the snow surface, preferentially removing molecules containing lighter isotopes and leaving the snowpack enriched in heavier isotopes. Meltwater percolation through the snowpack and refreezing at lower layers can also cause local enrichment as lighter isotopes are transported downward. These processes lead to greater isotopic variability and, in many cases, a net upslope enrichment over the course of the melt season, as was evident in the high-altitude snowpack samples of Sindh and on Lidder's southern slope by late season. The strong DOY dependence in Rambiara's snowpack ($R^2 \sim 0.91$) explicitly reflects how the accumulation of winter snow (with a distinct initial isotopic signature) and subsequent modification in spring/summer produce a predictable temporal change in isotopic content. Our findings reinforce that elevation and season must be considered together: the ILR is not constant year-round but can be seasonally augmented or suppressed by these post-depositional effects. This is in agreement with observations by Stewart (2009), who emphasized that models of isotope dynamics in mountain snowpacks should incorporate seasonal melt processes alongside altitude. In practical terms, applying a single "average" ILR without accounting for the seasonal phase (accumulation vs. melt) could lead to oversimplified or erroneous interpretations. Instead, incorporating time-evolving fractionation mechanisms—such as sublimation and meltwater percolation—enhances the accuracy of reconstructions of water sources and climatic conditions from isotopic data in high-altitude regions.

5.3 Preservation of meteoric signals and post-depositional effects

The alignment of our snow and snowpack samples along the Global Meteoric Water Line indicates that the original meteoric isotopic signature of precipitation is largely preserved in these high-elevation catchments (Gat, 1996). In general, fresh snowfall and even the snowpack water that ultimately feeds glacier melt showed δ^2H and $\delta^{18}O$ values that remain close to unaltered precipitation inputs. This suggests that despite some in-situ modifications, the dominant source signal (i.e., the composition imparted by atmospheric processes during condensation and precipitation) is still recognizable. Such preservation is likely due to the relatively short residence time of seasonal snow and the continual addition of new snowfall, which limit the extent of evaporative enrichment. We did observe minor deviations from the meteoric water line in specific cases, providing evidence of limited post-depositional alteration. A subset of snow samples from the Sindh catchment plotted slightly above the GMWL, hinting at subtle evaporation or sublimation effects on the surface snow in certain microclimatic conditions (Dar et al., 2024). These small positive δ^2H shifts imply that in some localized environments—perhaps areas with greater exposure to sun or wind—the snow underwent a degree of kinetic fractionation. Similarly, during the melt period, snowpack samples showed a marginal increase in scatter around the GMWL, consistent with the notion that meltwater percolation and refreezing can cause slight isotopic shifts within the snowpack (Zuecco et al., 2019). Importantly, these shifts were small: even in the melt-season snowpack, nearly all points remained close to the local meteoric water line, indicating only minor enrichment of heavy isotopes.

Crucially, the data did not exhibit any pronounced kinetic fractionation signatures, such as extremely low $\delta^2H/\delta^{18}O$ ratios that would indicate strong evaporative losses. Kinetic fractionation during processes such as prolonged sublimation under dry conditions can drive isotopic values far off the meteoric water line (Stichler et al., 2001), but our sample set did not show such behavior. The lack of a strong kinetic imprint suggests that conditions were generally not arid enough or exposure times not long enough for extreme evaporative enrichment to occur. It is likely that periodic snowfall and a relatively humid snowpack environment limited the extent of open-ended evaporation, thereby preserving the isotopic integrity of the snow. This outcome is encouraging for hydrological applications: it means that the isotopic composition of meltwater runoff in these catchments can be traced back to precipitation sources with a high degree of confidence since minimal isotopic "re-setting" has occurred in the snow. In essence, the snowpack acts as a near-conservative reservoir of the precipitation isotope signal (aside from slight enrichments at the surface), which simplifies the interpretation of meltwater isotopic data when distinguishing different water sources or inferring moisture origins.

5.4 Implications for hydrology and climate change

The insights gained from this study have several implications for regional hydrology and assessing the impacts of climate change. First, the pronounced catchment-specific differences in isotopic controls underscore the importance of developing localized calibrations for isotope-based hydrological models. Rather than assuming uniform lapse rates or isotopic behavior across the Himalayas, water resource assessments should account for factors such as aspect, albedo, and seasonal timing that we identified as critical in particular catchments. Incorporating these factors will improve the accuracy of models used to partition sources of streamflow (e.g., distinguishing rain, snowmelt, and glacial melt contributions) and to predict the timing and magnitude of meltwater release. For instance, knowing that south-facing slopes yield systematically heavier isotope signatures can help separate meltwater originating from those slopes in a mixing analysis.

Second, the observed seasonal and altitudinal variations in isotopic composition provide valuable indicators for climate change monitoring. As the climate warms and precipitation regimes shift, we expect changes in both the amount and the isotopic characteristics of snowfall and glacier melt. A warming climate could lead to a higher proportion of winter precipitation falling as rain instead of snow at lower elevations, potentially altering the average isotopic signature of the snowpack. Additionally, increased temperature-driven sublimation and melt rates might intensify the enrichment of heavy isotopes in the remaining snow, a signal that can be tracked over time as an indicator of enhanced ablation. Long-term isotopic measurements in snow and meltwater could thus serve as sensitive recorders of changing conditions: for example, a systematic trend toward heavier spring meltwater isotope values might indicate diminishing fresh snow inputs or more extensive sublimation from the snowpack year by year.

The isotopic data can also inform our understanding of glacier health and water resource resilience. Glaciers integrate isotopic inputs over multiple years; shifts in the isotopic composition of glacier meltwater could reflect changes in accumulation patterns (such as more summer precipitation or loss of winter snow due to warming). If future isotopic monitoring detects a departure from historical meteoric-line relationships, it may signal altered evaporation or melt processes linked to climate trends. Such information is critical for projecting future water availability in snow-fed river basins. Ultimately, our findings highlight that stable water isotopes, when interpreted with the knowledge of local controls, are powerful tools for detecting and attributing hydrological changes in remote mountain environments. By continuing to monitor isotopic signatures across different catchments and seasons, scientists and water managers can better anticipate the consequences of climate change on Himalayan water resources and develop more effective adaptation strategies for managing water supply in downstream communities.

6 Conclusion

This study investigated the isotopic composition of glacier melt, snow, and snowpack across three Himalayan catchments—Lidder, Sindh, and Rambiara—to assess how environmental variables and elevation influence δ^2H and $\delta^{18}O$ signatures. The analysis revealed that aspect, albedo, and temperature are key predictors of isotopic variability, although their influence varied across catchments and sample types. Aspect was particularly important in the Rambiara catchment, where snowpack isotopic composition was strongly governed by slope orientation, likely due to differential solar radiation exposure. In the Sindh catchment, the day of sampling (DOS) and temperature significantly affected snow isotopic signatures, highlighting the role of temporal and thermal processes. Albedo also emerged as a relevant control, particularly in the Sindh catchment. Altitude exerted a more complex and catchment-specific influence. In the Lidder catchment, glacier melt on northern slopes became increasingly depleted in heavy isotopes with elevation—consistent with classical altitude effects—while snow and snowpack on the same slopes exhibited mild enrichment, likely due to processes such as wind redistribution and sublimation. On the southern slopes, altitude had little effect on glacier melt and snow, suggesting isotopic homogenization due to melt-refreeze cycles. However, snowpacks on these slopes showed moderate enrichment with elevation, pointing to cumulative effects of sublimation and partial melting at higher altitudes. These results emphasize the necessity of high-resolution, catchment-specific approaches for interpreting isotopic data in complex mountain terrains. Environmental factors such as aspect, temperature, and elevation significantly shape isotopic patterns and should be incorporated into hydrological and climate models, especially in snow-dominated systems. Future research should focus on quantifying the role of microclimatic conditions, wind redistribution, and snow metamorphism in driving isotopic variability. Moreover, long-term monitoring and modeling are essential for understanding seasonal and altitudinal trends in isotopic enrichment and depletion. Such efforts will enhance the ability to predict meltwater contributions under changing climatic conditions and improve water resource management in Himalayan headwater basins.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

TD: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. NR: Funding acquisition, Resources, Supervision, Validation, Writing – review & editing. SK: Supervision, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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