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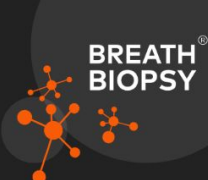
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Hydrological regimes and evaporative flux partitioning at the climatic ends of high mountain Asia

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E-mail: stefan.fugger@ist.ac.at**Keywords:** glacio-hydrology, high mountain Asia, high mountain hydrology, ecohydrology, landsurface modelling, remote sensing hydrologySupplementary material for this article is available [online](#)

Abstract

High elevation headwater catchments are complex hydrological systems that seasonally buffer water and release it in the form of snow and ice melt, modulating downstream runoff regimes and water availability. In High Mountain Asia (HMA), where a wide range of climates from semi-arid to monsoonal exist, the importance of the cryospheric contributions to the water budget varies with the amount and seasonal distribution of precipitation. Losses due to evapotranspiration and sublimation are to date largely unquantified components of the water budget in such catchments, although they can be comparable in magnitude to glacier melt contributions to streamflow. Here, we simulate the hydrology of three high elevation headwater catchments in distinct climates in HMA over 10 years using an ecohydrological model geared towards high-mountain areas including snow and glaciers, forced with reanalysis data. Our results show that evapotranspiration and sublimation together are most important at the semi-arid site, Kyzylsu, on the northernmost slopes of the Pamir mountain range. Here, the evaporative loss amounts to 28% of the water throughput, which we define as the total water added to, or removed from the water balance within a year. In comparison, evaporative losses are 19% at the Central Himalayan site Langtang and 13% at the wettest site, 24 K, on the Southeastern Tibetan Plateau. At the three sites, respectively, sublimation removes 15%, 13% and 6% of snowfall, while evapotranspiration removes the equivalent of 76%, 28% and 19% of rainfall. In absolute terms, and across a comparable elevation range, the highest ET flux is 413 mm yr⁻¹ at 24 K, while the highest sublimation flux is 91 mm yr⁻¹ at Kyzylsu. During warm and dry years, glacier melt was found to only partially compensate for the annual supply deficit.

1. Introduction

The mountain cryosphere is on a downward trajectory globally, as indicated by widespread declines in seasonal snowpack and negative glacier mass balances (Mudryk *et al* 2020, Hugonnet *et al* 2021). However, the importance of snow and glaciers as runoff contributors differs from basin to basin and depends on the local hydro-geographical setting (Bookhagen and

Burbank 2010, Lutz *et al* 2014, Immerzeel *et al* 2020, Kraaijenbrink *et al* 2021). In monsoonal basins, such as the Ganges–Brahmaputra, concurrent melt, snowfall and rainfall amplify seasonal streamflow variability (Khanal *et al* 2021). In semi-arid basins, such as the Amu-Darya river basin, glacier melt sustains streamflow during the summer gap in precipitation inputs (Unger-Shayesteh *et al* 2013, Sorg *et al* 2014, Pohl *et al* 2017, Pritchard *et al* 2019).

A number of processes other than glacier melt shape the mountain water budget, including the amount and seasonality of precipitation, snow cover dynamics, plant transpiration, surface evaporation and sublimation, all of which are highly variable in mountain environments. High vapour pressure deficits and radiative energy inputs drive the latent (LE) and sensible (H) energy fluxes. Cloudy conditions and elevated humidity can reduce turbulent heat fluxes by up to 70%, due to a more stable boundary layer under such conditions, resulting in a lowering of the evaporative fluxes (Mandal *et al* 2022).

Evaporative fluxes (E) are defined here to include all evaporation, transpiration and sublimation fluxes from the land surface ($E = ET + S$), while evapotranspiration (ET) and sublimation (S) are treated separately in this study.

Evapotranspiration (ET) represents a crucial mass loss from the hydrologic system, and is estimated to globally return around 60% of water inputs to the atmosphere over land (Seneviratne *et al* 2010, Katul *et al* 2012). However, despite its significance, ET has received limited attention in studies of high elevation catchments, which are extreme environments for vegetation. As an example, it remains elusive whether ET is a greater loss term in wet, monsoonal environments characterised by abundant water availability and energy limitations, or in semi-arid places with high energy inputs and potentially water limitations. ET is expected to increase with global warming due to greening and succession (e.g. Zhu *et al* 2016, Dütthmann and Blöschl 2018, Yang *et al* 2023), while sublimation is expected to decrease with reductions in snow cover and higher temperatures.

In High Mountain Asia (HMA), where sublimation studies are still scarce, many questions remain around sublimation rates at high elevation, its sensitivity to monsoonal conditions, interannual variability and the importance of ground, canopy intercepted, and blowing snow sublimation at the catchment scale (Stigter *et al* 2018, Mandal *et al* 2022, Potocki *et al* 2022, Buri *et al* 2023). Neglecting sublimation as a mass sink leads to erroneous estimates of melt rates and streamflow when snow and glacier mass balances are calibrated (Stigter *et al* 2018).

From the water balance perspective, ice melt and evaporative fluxes oppose one another in that ice melt generates runoff, whereas evaporative fluxes generally reduce runoff, while they are sensitive to similar meteorological variables. Modelling in the upper Langtang catchment has shown that the totals of ice melt and evaporative fluxes were comparable in magnitude during the 2018/19 hydrological year (Buri *et al* 2023). However, it remains unknown under which conditions increased glacier melt would also compensate for precipitation deficits and increased evaporative fluxes (Van Tiel *et al* 2021) at the seasonal scale in high-elevation catchments.

Serving as research tools, mechanistic models enable new process understanding and detailed quantification of flux partitioning and sensitivity to environmental changes (Poulin *et al* 2011, Mastrotheodoros *et al* 2019, Pomeroy *et al* 2022). Previous applications of such models have highlighted counter-intuitive relationships of ET and water availability, such as an inverse correlation of ET with precipitation under drought conditions (Mastrotheodoros *et al* 2020). Due to their physical basis, these models are regarded as robust across temperate, humid and sub-humid environments and under shifting boundary conditions, such as climate change and extreme events (Poulin *et al* 2011, Fatichi *et al* 2016, Pomeroy *et al* 2022).

In this study, an ecohydrological model geared towards high mountain hydrological systems is applied to three glacierized headwater catchments in contrasting climates within HMA to constrain the hydrological fluxes at high elevations. After a thorough evaluation of the model, the partitioning of mass and energy fluxes, together with ecohydrological variables, are investigated to determine the main components of runoff generation. We hypothesise that:

- (I) Sublimation is higher in semi-arid, high elevation catchments, where longer periods of cold and clear-sky conditions with high energy inputs occur.
- (II) ET is higher in monsoonal catchments due to the prevalence of concurrent periods of liquid water abundance and high temperatures, along with intensive vegetation coverage.
- (III) In warm and dry years, increased glacier melt fully compensates, or even overcompensates for precipitation deficits and enhanced evaporative losses.

2. Study sites

Three glacio-hydrological reference catchments are investigated, with the common features of steep topography, vegetation cover, substantial glacier coverage, abundance of supraglacial debris and large, but comparable elevation ranges (figures 1(a)–(e)). Since they span the climatic spectrum of HMA, these catchments are ideally suited for a comparative perspective on the diversity of HMA headwater hydrology.

Kyzylsu (KYZ, 168 km²) is located in the headwaters of the Amu Darya river basin, on the northernmost slopes of the Pamir mountain range in Tajikistan (figures 1(a) and (b)). The local weather is controlled by a continental climate and has no direct influence from the Indian summer monsoon (Schienmann *et al* 2008). Monitoring in this new reference catchment

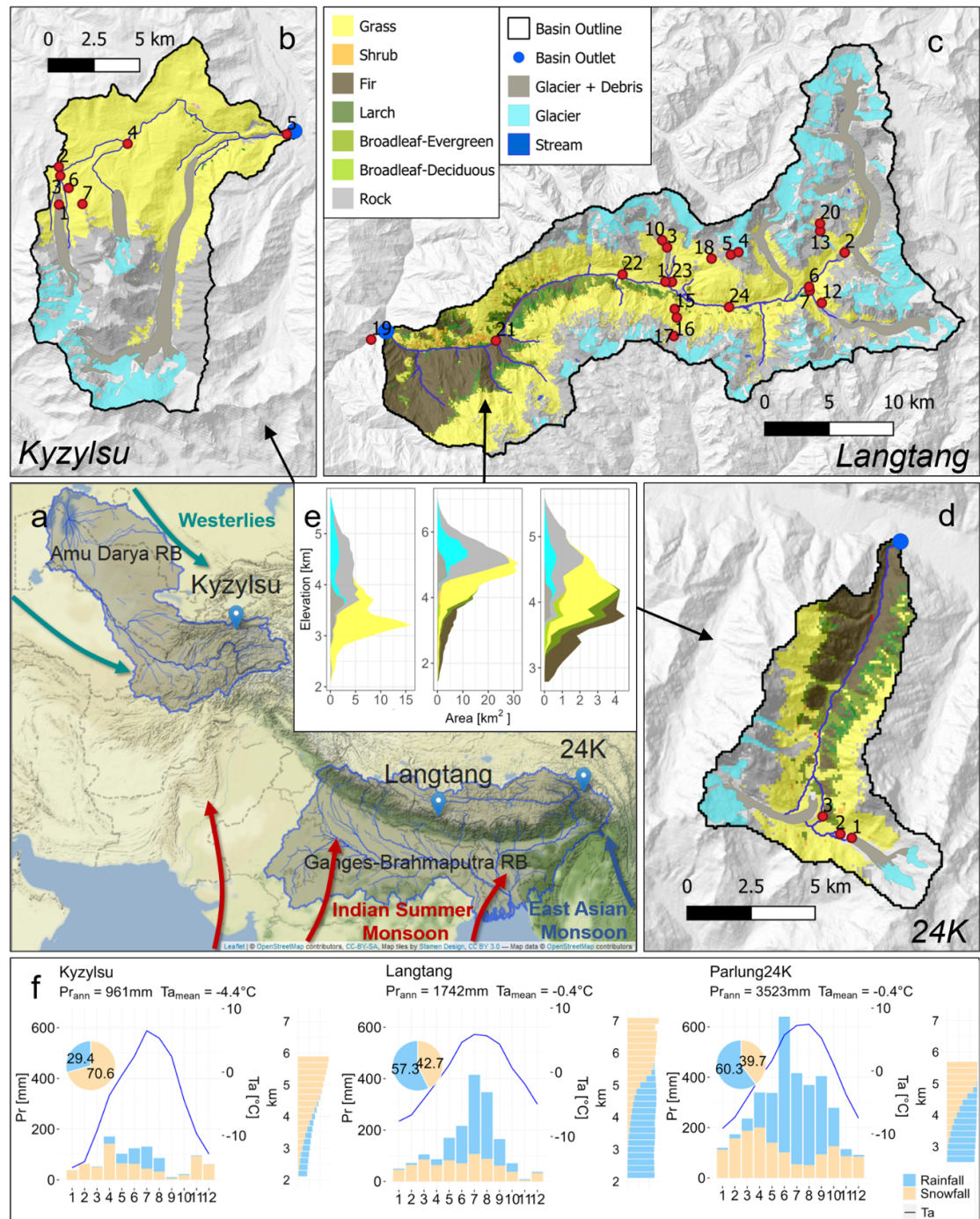


Figure 1. (a) Map of the region with the location of the three study catchments indicated, along with (b)–(d) detailed maps showing land cover and station locations and station identifiers. (e) Land cover hypsometry. (f) Average monthly meteorological conditions over the study period and hypsometry of precipitation partitioning.

has only recently started (June 2021), and observations were geared towards glacio-hydrological modelling. The initial network is detailed in supplementary section 1. The region, with a mean glacier mass balance of -0.17 m w.e. yr^{-1} (Pamir and Pamir Alai regions, 2000–2016, Miles *et al* 2021), has been regarded as part of the Pamir-Karakoram Anomaly (Hewitt *et al* 2005, Farinotti *et al* 2019, Barandun *et al* 2021, Miles *et al* 2021). Recent evidence however suggests that the region might be trending towards overall negative mass balances (Hugonnet *et al* 2021).

Located in the Central Himalaya of Nepal and seasonally governed by the Indian Summer Monsoon (figures 1(a) and (c)), *Langtang* (LAN, 586 km^2) is a well-studied Ganges headwater catchment, where monitoring has taken place since the 1980s, and systematic meteorological and glaciological measurements have been made since 2012 (e.g. Higuchi 1984, Fujita *et al* 1997, 1998, Steiner *et al* 2021). The region exhibits rapidly shrinking glaciers, with a mean mass balance of -0.43 m w.e. yr^{-1} (Everest region, 2000–2016, Miles *et al* 2021).

Parlung 24k (24 K, 64 km²), is a small Yarlung Tsangpo/Brahmaputra headwater basin on the Southeastern Tibetan Plateau (figures 1(a) and (d)) that has been monitored since 2016 (Yang *et al* 2017). Out of the three study sites, it has the wettest climate, with heavy precipitation occurring from March to September (figure 1(f)), since it is affected by both the Indian and East Asian summer monsoons (Bookhagen and Burbank 2010, Ding and Chan 2005). Glacier mass balances in the region have been shown to be amongst the most negative in HMA, averaging around $-0.68 \text{ m w.e. yr}^{-1}$ (Nyainqentangla region, 2000–2016, Miles *et al* 2021), which has been partly attributed to a shift in precipitation from snowfall to rain (Jouberton *et al* 2022).

3. Methods

3.1. The model

To simulate the coupled dynamics of water, snow and glaciers, energy, vegetation physiology and carbon in the three catchments, the Tethys-Chloris model (T&C; Fatichi *et al* 2012a, 2012b, Manoli *et al* 2018, Mastrotheodoros *et al* 2019, Botter *et al* 2021, Paschalis *et al* 2022) (figure S3), was applied to the period October 2010 to September 2022. The period October 2010 to September 2012 was considered a spin-up period and was not included into the analysis of model outputs. For each grid cell, the energy balance is solved for the surface temperature of any type of land cover, including vegetated and bare land, rock, surface water, snow, glaciers and supraglacial debris, and includes the computation of net radiation, sensible and latent heat, heat consumed by photosynthesis and heat exchange with the subsurface. The model also resolves infiltration and exfiltration, deep percolation, lateral surface and subsurface water flows, soil moisture dynamics in the unsaturated zone including root water uptake at different depths at the grid level. Glaciers are represented as a single-layered ice-pack including a retention capacity for water. Glacier outlines and debris covered areas were manually corrected, based on the Randolph glacier inventory (RGI-6) and the debris thicknesses product was prepared combining remote sensing data and in-situ observations (supplementary section 4). The snow-, ice and ice-under-debris mass balance models are described in detail in Fugger *et al* (2022) and Fyffe *et al* (2021). A more detailed description of T&C is provided in Fatichi *et al* (2012a, 2012b, 2020), and a setup in the upper part of Langtang and additional model details are described in Buri *et al* (2023). Advances implemented for this study include a 2-layer snowpack model, where the surface energy balance is solved at a skin layer, and a parameterization for glacier geometry changes as detailed in supplementary section 5. The sensitivity of the energy and mass fluxes involved in the computation of the

glacier and snow mass balances to model parameters and meteorological forcing were presented in Fyffe *et al* (2021) and Fugger *et al* (2022).

The model parameters were not calibrated in the traditional sense, e.g. through automatic calibration of multiple parameters against spatially integrated variables like runoff. Instead they were estimated from the literature and using expert knowledge (e.g. Fatichi *et al* 2016). Parameters requiring optimization and manual adjustments from the T&C standard setup were related to the thermal properties of the supraglacial debris, the glacier geometry updates, bare-ice albedo, the vegetation phenology and to high-elevation precipitation at one of the sites (supplementary section 5).

3.2. Forcing data

The model was forced using downscaled hourly air temperature (T_a), relative humidity (RH), total precipitation (P), incoming shortwave radiation (S_{in}), incoming longwave radiation (L_{in}), wind speed (W_s) and air pressure (Pa) data from the ERA5-Land 9 km reanalysis (Muñoz-Sabater *et al* 2021). Statistical downscaling to 100 m spatial resolution was performed following the approach of Machguth *et al* (2009), which combines simple parameterisations with spatial interpolation (supplementary section 2, figures S1 and S2). Bias correction of forcing variables was performed using empirical quantile mapping against local station data (supplementary section 3). Independent stations were used, where possible, to assess the efficacy of the bias-correction in space and time (figures S4–S21). Despite minor discrepancies, the forcing data are deemed acceptable for the representation of spatial and temporal variability in the catchment-wide meteorology, as indicated by low biases, RMSE values and high correlation coefficients against observations (figures S4–S21, table S3).

3.3. Model evaluation

Model performance was evaluated using a combination of in-situ and remote sensing data. Snowlines were derived from the MODIS Terra snow cover V6.1 product (Fugger 2018, Hall and Riggs 2021) and compared to the modelled snowlines. Snow cover was additionally evaluated scene-by-scene against Sentinel-2/Landsat-8 and Dice coefficients (Dice 1945) were calculated. The modelled surface mass balance of glaciers was evaluated against two references: the geodetic mass balance results of Hugonnet *et al* (2021); and altitudinal values derived following the approach of Miles *et al* (2021) that uses the thinning data of Hugonnet *et al* (2021) and the surface velocities of Millan *et al* (2022) at Langtang. At Kyzylsu and 24 K the velocity and geodetic mass balance data quality prevented the second approach. Modelled snow depth (all sites) and ice melt (Kyzylsu,

Langtang) were evaluated using automatic measurements of surface height. Catchment mean leaf area index (LAI) was compared against MODIS (MCD15A3H v.6, Myneni *et al* 2015) and VIIRS (VNP15A2H v.1; Myneni and Knyazkhin 2018) LAI products. Modelled discharge was evaluated against data from gauging stations in proglacial streams of Kyzylsu, Langtang and 24 K glaciers.

4. Results

4.1. Evaluation of model performance

Modelled snowlines correspond well with remote sensing observations are typically within the uncertainty ranges of the observed snowlines, with biases (R^2 values) of -52.2 m (0.74), -16.6 m (0.43), -194.4 m (0.41) for Kyzylsu, Langtang and 24 K, respectively (figure S22).

Modelled snow cover agreed well with Landsat-8/Sentinel-2 scenes in a scene-by-scene comparison, and average Dice coefficients for each site were 0.66, 0.66, 0.76 (figure S23), with higher performance during periods of more extensive snow cover and lower performance during patchy snow cover.

Compared to observations, the timing of local snow accumulation and glacier melt was very well reproduced, while some under- and overestimations of the snowpack height up to 45 cm occurred at 24 K and Kyzylsu (figure S24). These local discrepancies are likely related to the absence of a wind-driven snow redistribution scheme in the model.

The model agrees very well with the remote-sensing-based glacier-wide and altitudinal mass balance values at Langtang (0.65 m w.e.yr $^{-1}$ vs 0.62 ± 0.13 m w.e.yr $^{-1}$), to within observational uncertainty at 24 K (-0.42 m w.e. yr $^{-1}$ vs 0.25 ± 2.07 m w.e. yr $^{-1}$), and with a slight negative overestimation at the Kyzylsu glaciers (-0.46 m w.e. yr $^{-1}$ vs 0.18 ± 0.22 m w.e. yr $^{-1}$) (figures S25–S27).

LAI values show overall good agreement with observations in terms of magnitude (figure S28), while there are mismatches in terms of timing at Kyzylsu (RMSE: 0.52) and Langtang (0.71) and peak LAI magnitudes at 24 K (0.36).

Both the magnitude and timing of streamflow variations are well reproduced at the pro-glacial stream gauges, with NSE values of 0.5 at Kyzylsu, 0.55 at 24 K, and a somewhat weaker agreement at Langtang with 0.27 (figure S29).

4.2. Precipitation determines the relative importance of evaporative fluxes and glacier melt

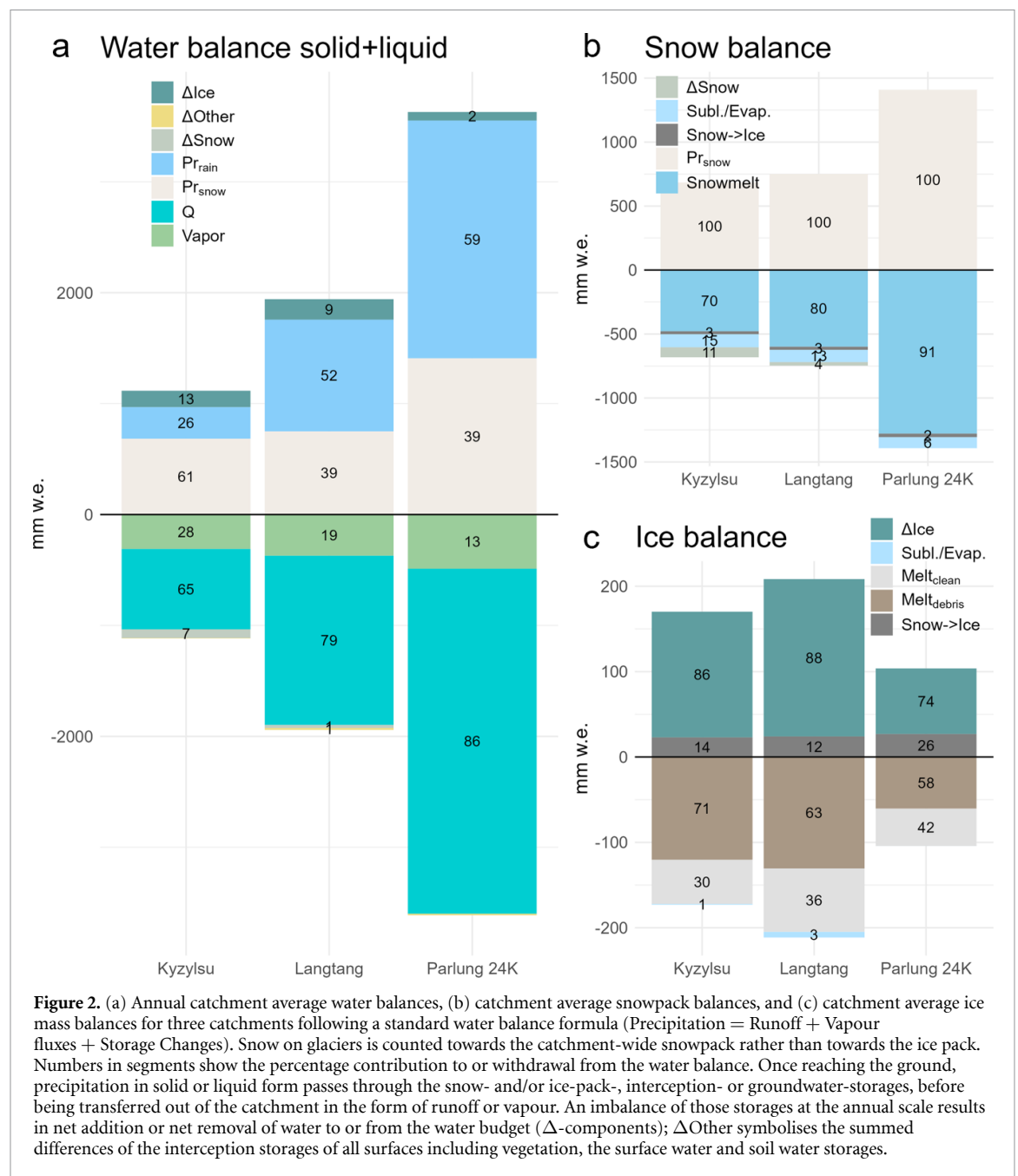
The annual water throughput of the catchments, which is defined as the total water added to or removed from the water balance within a year in either liquid, solid or gaseous form, increases from west to east (figures 2 and 5). The annual water

throughput is highest in 24 K, followed by Langtang and Kyzylsu: Langtang and 24 K respectively receive around 1.8 times (1742 mm yr $^{-1}$) and 3.7 times (3523 mm yr $^{-1}$) more precipitation than Kyzylsu (961 mm yr $^{-1}$) (figures 2 and 5). The partitioning of inputs into rain and snowfall is controlled by the precipitation seasonality: with a winter-accumulation regime, 70.6% of annual precipitation falls as snow at Kyzylsu, while those portions are smaller in Langtang (42.7%) and 24 K (39.7%) (figure 1(f)), where the bulk of the precipitation falls in the summer half-year.

Across the common elevation range of the three catchments (2500–5700 m asl), snowmelt contributes 67% of annual runoff in Kyzylsu, 35% in Langtang, and 41% in 24 K (figure 3(a)). Once most of the snow has melted out in Kyzylsu between the middle and end of August, ice melt becomes the dominant runoff contribution with 55% in September (annually 24%). In Langtang, which has a similar proportion of glacier area, the ice melt contribution peaks in post-monsoon with 21.7% in October, while later during summer, it is dwarfed by monsoonal rainfall so that the ice melt contribution is only 14% annually. At 24 K, which hosts around half the proportion of glacier area compared to the other sites, but gets substantially higher liquid precipitation inputs, ice melt contributes only 8% to the runoff in August (3% annually) (figure 3(a)). Note that snowmelt above glacier surfaces is counted towards the catchment-wide snowmelt rather than to the ice melt.

Rainfall runoff contributes the largest share (56%) to total runoff in 24 K, followed by Langtang (51%), and Kyzylsu (9%) (figure 3(a)). During the period March to August rainfall is transformed into runoff in Kyzylsu, while from September to October the majority of rainfall is evaporated (figure 3(a)).

In all three catchments, catchment-wide, modelled glacier mass balances were negative over the study period with -0.46 , -0.65 and -0.42 m w.e. yr $^{-1}$ in Kyzylsu, Langtang and 24 K respectively (figures S25–S27). The imbalance melt, defined as the glacier melt not replenished by new ice formation, accounted for 13, 9 and 2% of the mass inputs to the water balance in Kyzylsu, Langtang and 24 K, respectively (figure 2). In all catchments, sub-debris ice melt is larger than bare-ice melt, with 66.8, 62.5, 57.9% for Kyzylsu, Langtang and 24 K, respectively (figure 2). The total E (combined ET and S) accounts for 28, 19 and 13% of the catchment water output (figure 2(a)) of Kyzylsu, Langtang and 24 K, respectively. ET alone corresponds to 76% of the liquid precipitation falling in Kyzylsu, 28% in Langtang, and 19% in 24 K. The relative importance of glacier melt and evaporative fluxes therefore decreases with an increasing water throughput from west to east. A spatial distribution



of annual melt, evapotranspiration and sublimation is shown in figure S30.

4.3. Net radiation is the main control on evaporative fluxes at all sites

Across the common elevation range, the evaporative fluxes follow the seasonality of net radiation (R_n) that is available for the turbulent heat transfer in the case of ET and additionally the snow covered area and temperature regime in the case of S (figure 3(b)). Soil water limitations do not affect the ET rates in either of the catchments during average years, since the latent energy (LE) and ET follow the R_n regime throughout the season, and soil water limitations do not occur, as indicated by the soil moisture seasonality (figure 3(b)). A high availability of intercepted

water on leafs and rock surfaces however boosts evaporation rates in the wet climate of 24 K (figure 3(b)). Evaporation from supraglacial debris is a small flux for the catchment (not shown), but helps insulate the glacier ice by removing energy in the form of LE from entering the glacier (Fugger *et al* 2022).

4.4. Sublimation is important, especially at the semi-arid site

In all three catchments, sublimation removes mass from the ground and canopy intercepted snowpack year-round (figures 3(b) and (c)). Relative to the snowfall amounts, sublimation is largest in Kyzylsu, followed by Langtang and 24 K (15, 13, 6%, respectively) (figure 2(b)). In absolute terms and for the common elevation range, sublimation is also largest

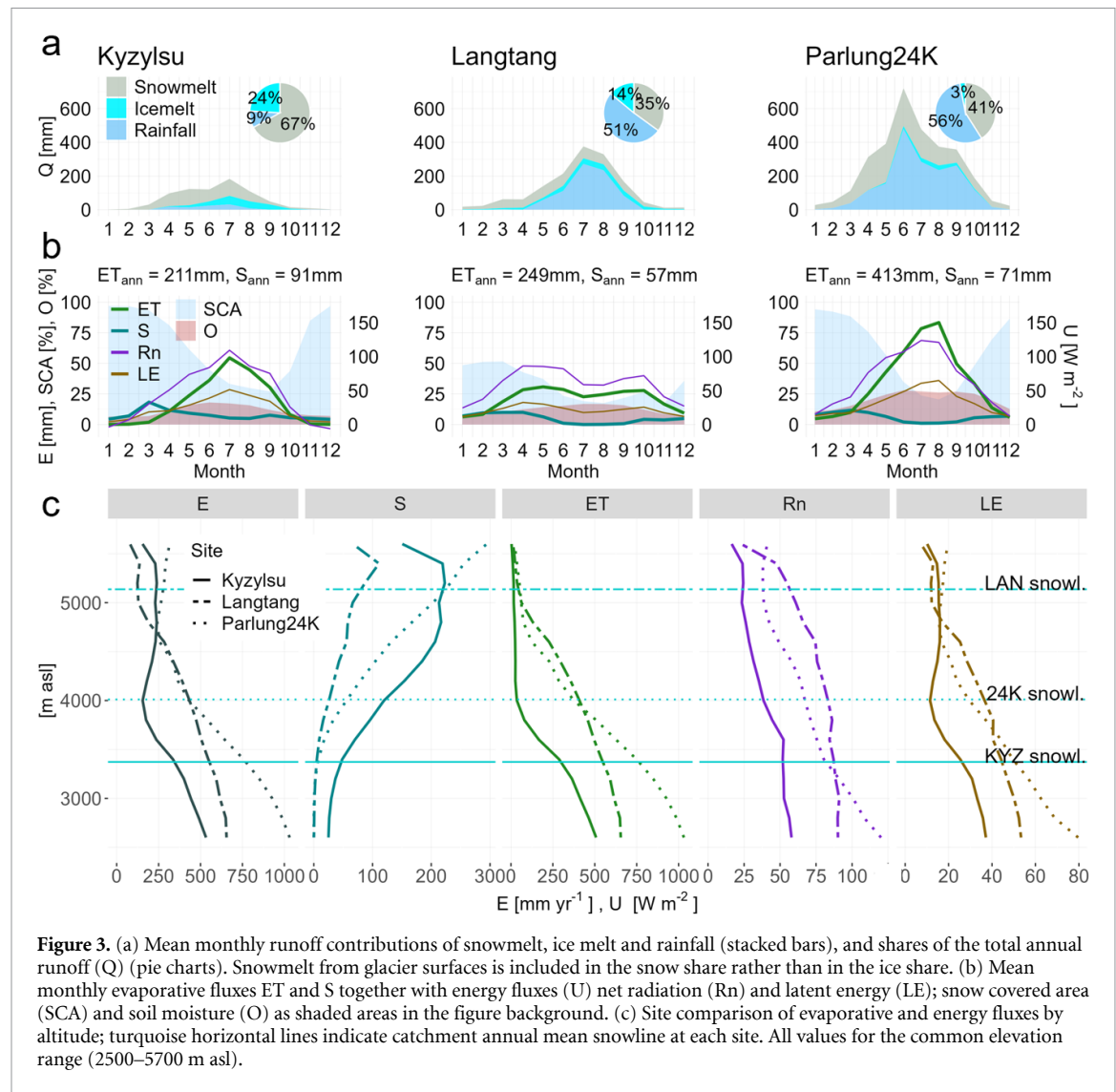


Figure 3. (a) Mean monthly runoff contributions of snowmelt, ice melt and rainfall (stacked bars), and shares of the total annual runoff (Q) (pie charts). Snowmelt from glacier surfaces is included in the snow share rather than in the ice share. (b) Mean monthly evaporative fluxes ET and S together with energy fluxes (U) net radiation (R_n) and latent energy (LE); snow covered area (SCA) and soil moisture (O) as shaded areas in the figure background. (c) Site comparison of evaporative and energy fluxes by altitude; turquoise horizontal lines indicate catchment annual mean snowline at each site. All values for the common elevation range (2500–5700 m asl).

in Kyzylsu (91 mm yr^{-1}), but it is second largest in 24 K (71 mm yr^{-1}) and smallest in Langtang (57 mm yr^{-1}). In Langtang, however, where the snowline is generally higher, most sublimation happens above the elevation range of the other basins, amounting to 84 mm yr^{-1} over the whole elevation range of Langtang (figure S32).

During the warmest months of the year, sublimation rates are low (e.g. Kyzylsu 0.2 mm d^{-1} , Langtang $<0.01 \text{ mm d}^{-1}$, Parlun24K 0.03 mm d^{-1}), since snow retreats to the highest elevations, and temperatures are often above the melting point during the periods of high radiation inputs, favouring snow and ice melt rather than sublimation (figure 3(c)). Only in Kyzylsu there is notable snowpack sublimation also in the lower reaches of the catchment, owing to the lower temperatures and heavier snowfalls there during winter (figure 3(c)).

4.5. Melt partially compensates for supply deficits in warm-dry years

Under warmer- and drier-than-average conditions, such as during the hydrological years 2021/22

(Kyzylsu) and 2016/17 (Langtang) and 2017/18 (24 K), additional ice melt of +35 mm, +33 mm and +10 mm partially compensates for the supply deficits. The supply deficit is here defined as the combination of precipitation deficits and ET losses, which amount to -225 mm , -153 mm and -368 mm compared to the multi-year average (2010/11–2021/22), at Kyzylsu, Langtang and 24 K, respectively (figure S31). Snowmelt under warm conditions has an even greater replenishing effect on the water yield, since old snow, e.g. from glacier accumulation zones, is being depleted: the snowmelt deficit (-32 mm , -22 mm , -170 mm) is considerably smaller than the snowfall deficit (-141 mm , -61 mm , -236 mm) (figure S31), implying a net snowmelt increase of 109 mm, 39 mm and 66 mm. While ice melt alone offsets only around 16%, 22% and 3% of the supply deficits, the ice and snow melt enhancements together offset 64%, 47%, and 21% of the precipitation deficits. As a result of compensations due to enhanced glacier and snow melt, the driest and warmest hydrological years (such as 2021/22 at Kyzylsu, 2016/17 at Langtang and

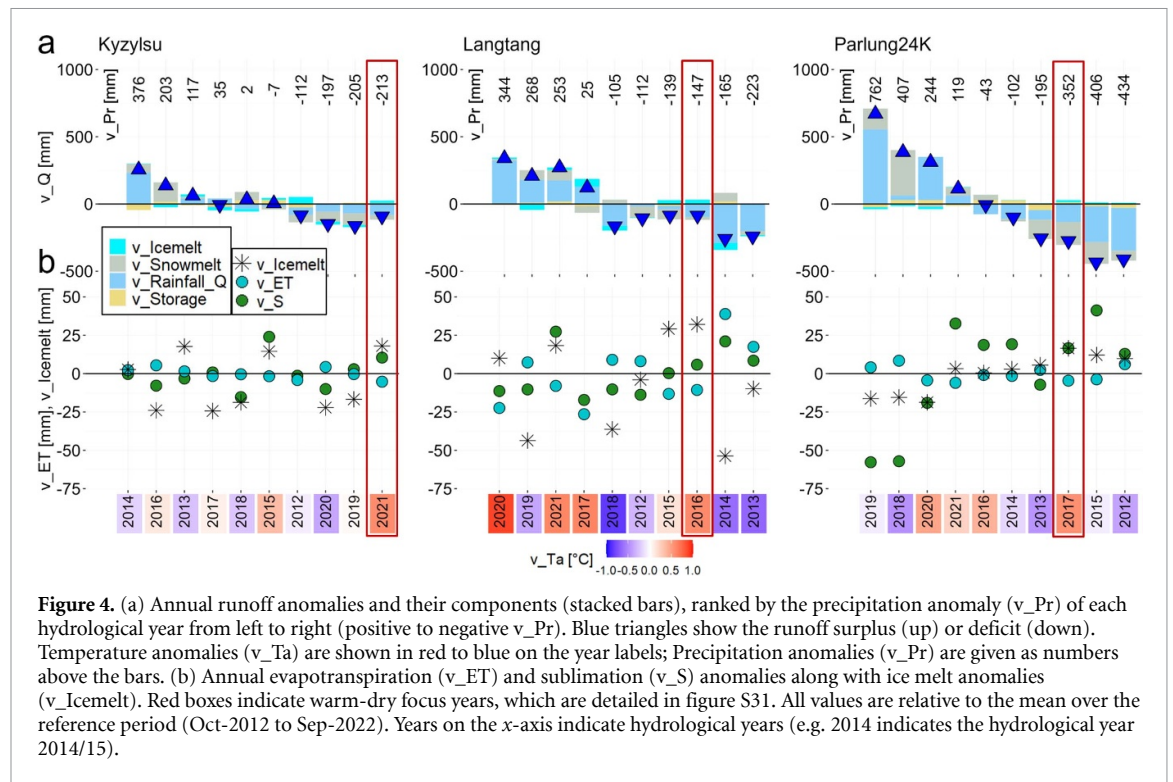


Figure 4. (a) Annual runoff anomalies and their components (stacked bars), ranked by the precipitation anomaly (v_{Pr}) of each hydrological year from left to right (positive to negative v_{Pr}). Blue triangles show the runoff surplus (up) or deficit (down). Temperature anomalies (v_{Ta}) are shown in red to blue on the year labels; Precipitation anomalies (v_{Pr}) are given as numbers above the bars. (b) Annual evapotranspiration (v_{ET}) and sublimation (v_S) anomalies along with ice melt anomalies ($v_{Icemelt}$). Red boxes indicate warm-dry focus years, which are detailed in figure S31. All values are relative to the mean over the reference period (Oct-2012 to Sep-2022). Years on the x -axis indicate hydrological years (e.g. 2014 indicates the hydrological year 2014/15).

2017/18 at 24 K) do not correspond to the greatest runoff deficits (figure 4(a)).

Evapotranspiration anomalies can reach values similar to those of enhanced ice melt under warmer conditions (e.g. Kyzylsu: 2015, 2021; Langtang: 2021; 24K: 2017; figure 4(b)), implying that evapotranspiration counterbalances the additional ice melt contribution to streamflow. Note however, that the level of this balancing is strongly related to the proportion of glacier cover versus the remaining land cover in a catchment.

5. Discussion

5.1. Importance of evapotranspiration and sublimation

Sublimation is highest in both relative and absolute terms and across the common elevation range in Kyzylsu, supporting our first hypothesis (I) that sublimation is most important in semi-arid, high elevation catchments (figures 2 and 3). Clear-sky conditions, with low winter temperatures and high snowfall rates create favourable conditions for sublimation. In contrast, cloudy, warm conditions during the accumulation period drastically reduce sublimation but favour melt (Mandal *et al* 2022, Fugger *et al* 2022). Snow sublimation has long been recognized as an important mass flux in snowy alpine environments, including in the Alps (Strasser *et al* 2008), glacierized catchments in the Canadian Rockies (Pradhanga *et al* 2022, Aubry-Wake *et al* 2022), the Himalaya (Buri *et al* 2023), and at the glacier scale in the Andes (Ayala

et al 2017). The share of snowfall removed by sublimation ranges between 5% and 90% in previous literature, depending on the study site's environment, elevation range and topography. Here, we estimate this share for the three catchments as 15% (Kyzylsu), 13% (Langtang) and 6% (24 K). Modelling scenarios not including sublimation would overestimate the annual snowmelt runoff by this share, affecting especially summer season runoff and peak flows (Stigter *et al* 2018).

Our second hypothesis (II), that ET is higher in monsoonal catchments, can also be confirmed, since Kyzylsu shows less overall ET than Langtang and 24 K. This is mostly a result of the energy regimes and snow cover dynamics, rather than a result of soil water limitations (figure 3). However, intense rainfalls over the greater part of the year provide additional water to evaporate from leaf-, rock- and other interception-storages, boosting ET at 24 K.

5.2. Trade-offs between ice melt and evaporative fluxes under warm-dry conditions

In none of the catchments and years did ice melt alone overcome the supply deficit during warm-dry years, although this may happen at the seasonal or event timescale (Van Tiel *et al* 2021). While ice melt enhancements reach similar magnitudes as the evaporative loss enhancements, the third hypothesis, that ice melt can compensate for the combination of both precipitation deficits and enhanced evaporative losses during warm-dry years, is not supported by our results. Ice melt combined with melt from old snow can however offset as much as 64% of the

supply deficit in Kyzylsu. These results reveal important implications for the system behaviour under climate change and should contribute to the discussion around future water yield under a vanishing cryosphere (e.g. Immerzeel *et al* 2013, Ragettli *et al* 2016, Huss and Hock 2018, McCarthy *et al* 2022).

5.3. Sensitivity to climate change

The interannual anomalies of sublimation and evapotranspiration can reach similar magnitudes as the ice melt anomalies (figure 4(b)), depending on the catchment configuration. The interannual variability in evaporative fluxes is generally smaller than the interannual variability of rain- and snowfall inputs at all sites, in agreement with previous studies (Roberts 1983, Fatichi and Ivanov 2014). Under a warming climate, therefore, shifts in precipitation volume and phase (Jouberton *et al* 2022, Shaw *et al* 2022), as well as the decline in glacier cover will probably be more important to streamflow variability (e.g. Ragettli *et al* 2016, Huss and Hock 2018) than changes in the evaporative fluxes. The streamflow at the semi-arid site is likely the most sensitive to climate change, due to the important role of the cryosphere in runoff generation for two reasons: (i) glacier melt sustains summer runoff and glaciers are shrinking, even in the domains affected by the Pamir–Karakoram anomaly (Hugonnet *et al* 2021). Where ‘imbalance’ ice melt at present compensates for runoff deficits under warm-dry conditions, this effect will initially increase, but eventually vanish, once ice masses have shrunk further (e.g. McCarthy *et al* 2022); (ii) Our analysis shows that the melting of old snow can buffer streamflow deficits during warm-dry years to an even greater extent than the melting glacier ice, with the highest degree of compensation at Kyzylsu. These old snow reserves would however vanish quickly over a few consecutive warm-dry years. Additionally, seasonal snowpacks are thinning and global warming is bringing the bulk snowmelt events earlier in the season (Unger-Shayesteh *et al* 2013). Modelling experiments based on future scenarios are needed, in order to fully understand the High Mountain Asian headwaters’ sensitivity to climate change.

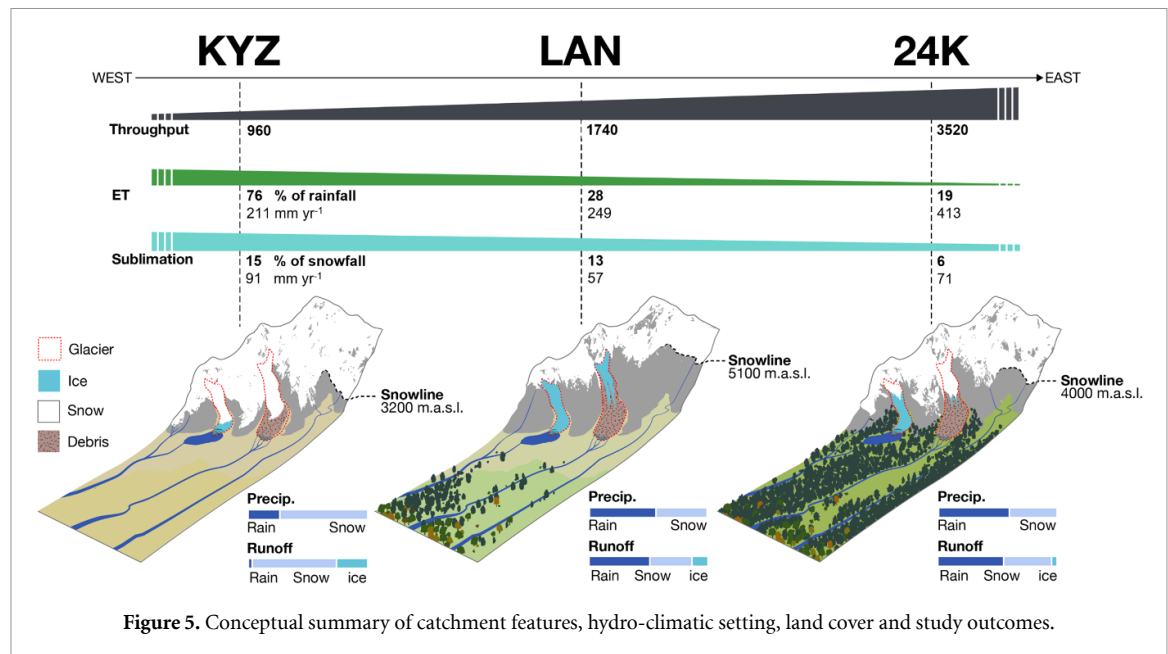
5.4. Limitations

Uncertainties in model outputs were not explicitly quantified due to the high computational demand of the model (table S4) limiting our ability to perform a large number of simulations. Instead, the model results were compared against a large range of ground and remotely sensed data, confirming its ability to replicate the necessary physical processes. While sublimation from the ground- and canopy-intercepted snowpack is simulated, blowing snow sublimation is not, and so sublimation on wind-exposed mountain ridges is potentially underestimated in this study (Strasser *et al* 2008). Similarly, due to the absence of a blowing snow transport scheme, the heterogeneity

of snow depths between ridges and valleys is under-represented (Aubry-Wake *et al* 2022). The model does not have a separate firn layer representation. This might affect the mass balance of the accumulation zones, since the thermal and surface properties of firn differ from those of snow and ice (Pradhanga and Pomeroy 2022). Supraglacial ice cliffs and ponds were not modelled, but these features are expected to enhance melt-rates of debris-covered glaciers (Miles *et al* 2018, 2022, Buri *et al* 2021, Kneib *et al* 2022). Finally, measurements of the surface latent heat fluxes are needed to better evaluate these fluxes in high elevation catchments and should be a goal of future fieldwork.

6. Conclusion

Our mechanistic modelling approach, forced with downscaled reanalysis data at a spatial resolution suited to steep mountain topography, proved transferable across three glacierized catchments, which span the geographic and climatic spectrum of HMA. Minimising the risk of equifinality issues, our approach requires minimal calibration, and addresses several key challenges for this domain (Azam *et al* 2021): a detailed representation of supraglacial debris and an energy-balance based calculation of ice melt under debris cover, bias-corrected and spatially variable meteorological inputs, the computation of sublimation, as well as evapotranspiration and all-surface-evaporation. Our simulations show that water throughput determines the importance of the evaporative fluxes, and varies by a factor of 3.7 between the ‘climatic ends’ of HMA studied here (Kyzylsu vs. 24 K, figure 1). We find that over the 10 year study period, sublimation losses accounted for an average of 15, 13 and 6% of the snow falling in Kyzylsu, Langtang and 24 K, respectively. They are highest at the site with the largest amount of winter and spring accumulation, Kyzylsu, also in absolute terms (figure 5). Evapotranspiration removes 76, 28 and 19% of the liquid precipitation from the three catchments, respectively, and prevents almost any runoff generation from rainfall during the low-flow months in Kyzylsu. However, annual evapotranspiration is highest in absolute terms at 24 K (figure 5). Ice compensates for up to 17% of the supply deficit during a warm, dry year at the site with the highest glacier cover, Kyzylsu, but neither fully, nor over-compensates at the annual timescale and in either of the catchments. Old snow melt and ice melt combined, however, can offset as much as 64% of the supply deficit. Increased evapotranspiration during those years can reach similar magnitudes to the additional ice melt, intensifying the deficit in the runoff. In order to better anticipate future water yields, the sensitivity of HMA headwaters to global warming should be further tested with experiments using mechanistic models.



Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: [10.5281/zenodo.10407300](https://doi.org/10.5281/zenodo.10407300).

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Conflict of interest

The authors declare no conflicts of interest in relation to this research paper.

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