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Glacier meltwater has limited contributions to the total runoff in the major rivers draining the Tibetan Plateau



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The Tibetan Plateau is the headwaters of several major river basins, but uncertainties exist in the estimated contributions of glacial melt and groundwater to runoff. We present a new tracer-aided glacio-hydrological model constrained by multiple datasets for five major river basins of the Tibetan Plateau. We show that the contribution of glacier melt to the annual runoff is less than 5% in all the five basins at the outlets—much less than previous estimates. Our secondary finding is that the partitioning between surface runoff and groundwater flow varied greatly across the watersheds, with groundwater runoff contributing 35–75% of the annual runoff. The contribution of glacier melt has a strong spatial variability and scale dependency, but the population heavily dependent on it is limited, so a potential significant decrease in water resources due to glacier shrinkage is not a problem that should raise public worries in the Tibetan Plateau.

The Tibetan Plateau is the source region of several large and important rivers, sustaining the ecosystems and providing essential water resources for the ~2 billion people in downstream regions¹. As a high mountainous region influenced by snow and ice, the hydrology is driven by multiple runoff source components (rainfall, snowmelt, glacier melt) and complex hydrological processes². Since different runoff components respond to climate change differently, quantifying the contributions of runoff components is essential for understanding and predicting runoff changes, now and into the future³.

But quantifying runoff components on the Tibetan Plateau has yielded highly equivocal results. Some studies have shown that glacial melt has caused significant water imbalances (i.e., by reducing water storage)^{4,5} in this region, but there is little agreement about its contribution to runoff change, and at what extent this imbalance influences the river discharge. In the upper Brahmaputra (a typical large mountainous river on the Tibetan Plateau), the contribution of glacier meltwater to the annual runoff has been

reported to range from 3.5% to 29%^{6–8}. A major difficulty in pinning down this number is the complexity of the hydrological processes and the difficulty in representing them in a model; itself suffering often from a lack of data for model calibration and validation^{9–11}.

Most previous model-based studies have been constrained solely by the in situ streamflow discharge data, which only reflects the “celerity” of water flow, i.e., the speed at which changes in input water propagate to the output through the system. This results in a lack of the “velocity” reflecting the actual water movement, which is more relevant for tracing the water sources and pathways of runoff components¹². Past modeling efforts, too, have suffered from a lack of validation of the cryospheric process simulations¹³.

While many efforts have been made to quantify the proportion of multiple water sources (i.e., whether water comes from rainfall or snow/glacier meltwater) in this region, little attention has been paid to separating the runoff into different pathways (i.e., surface runoff and groundwater), which reflects the runoff generation mechanisms—crucial to the issues of

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water resources, ecohydrological processes and cryospheric responses to the climate change^{14–16}. Due to the different model structures and inadequate validation of groundwater flow processes, these estimates remain highly uncertain with, for instance, the contribution of groundwater ranging from 4% to >80% in the upper Brahmaputra basin^{8,13}.

Recently, hydrological models have been developed that integrate key cryospheric processes (accumulation/melting of snow and glacier ice) and high-quality datasets representing these processes (e.g., snow cover area, glacier elevation change)^{17,18}. They now provide an opportunity to estimate the contribution of these water sources to runoff on the Tibetan Plateau. The use of combined tracer-aided hydrological models and the isotopic general circulation models together provides the potential to reduce model uncertainty and to increase parameter identifiability, especially for estimates of the contribution of runoff components with different travel times^{19–21}.

Here we build on these exciting new developments and present a new tracer-aided glacio-hydrological model to simulate the hydrological, cryospheric, and tracer processes of the large river basins of the Tibetan Plateau. We focus on the contribution of runoff components (a detailed explanation on their definition is provided in the Methods section) in the five major rivers draining the Tibetan Plateau at their gauging stations closest to the boundary of Tibetan Plateau (Upper Brahmaputra: $2.1 \times 10^5 \text{ km}^2$, $61 \pm 8 \text{ km}^3/\text{yr}$, 1.6% glacier coverage; Upper Salween: $1.1 \times 10^5 \text{ km}^2$, $55 \pm 6 \text{ km}^3/\text{yr}$, 1.2% glacier coverage; Upper Mekong: $8.8 \times 10^4 \text{ km}^2$, $31 \pm 4 \text{ km}^3/\text{yr}$, 0.3% glacier coverage; Upper Yangtze: $1.4 \times 10^5 \text{ km}^2$, $16 \pm 3 \text{ km}^3/\text{yr}$, 0.7% glacier coverage; and Upper Yellow: $1.2 \times 10^5 \text{ km}^2$, $21 \pm 5 \text{ km}^3/\text{yr}$, 0.1% glacier coverage). These drainages for each basin have been used frequently in previous studies on the Tibetan Plateau because of the relatively high-quality streamflow gauging stations (Nuxia, Daojueba, Jiuzhou, Zhimenda, and

Tangnaihai for the study rivers). We quantify the contribution of runoff components based on two definitions: input water source definition quantifying where the input water forcing the hydrological processes comes from (rainfall, snowmelt and glacier melt), and runoff generation pathway definition quantifying whether the input water generate runoff through surface pathway (saturation overland flow, infiltration excess overland flow and direct runoff occurring in river channels) or subsurface pathway (groundwater outflow and interflow) (see Methods and Supplementary for details and diagram representation). Our main questions are: (1) What is the contribution of glacial meltwater to annual flows? (2) What is the contribution of different pathways that generate runoff? (3) What is the spatial pattern of the runoff component contributions within five basins, and how does it vary with the meteorological and geographical conditions? To answer these questions, we built a state-of-the-art tracer-aided glacio-hydrological model in the five basins and, for the first time, utilized multiple datasets including streamflow, snow cover area, glacier elevation change, and stream water isotopes to calibrate the model.

Results

Contribution of multiple runoff components

Our first research finding is that the contribution of glacier melt to the annual runoff is less than 5% in all the five basins of the Tibetan Plateau (Figs. 1 and 2)—much less than most previous estimates (e.g., 12–29% for the Upper Brahmaputra basin with most glacier coverage)^{3,6,22,23}. Rainfall is the dominant water source, contributing 74–87% to the total water input. The contribution of snowmelt is around 15% in the four basins, except the Upper Yangtze basin, where the snowmelt contributes 23% of the total water input. While the contribution of glacier melt to the annual runoff is less than 5% in

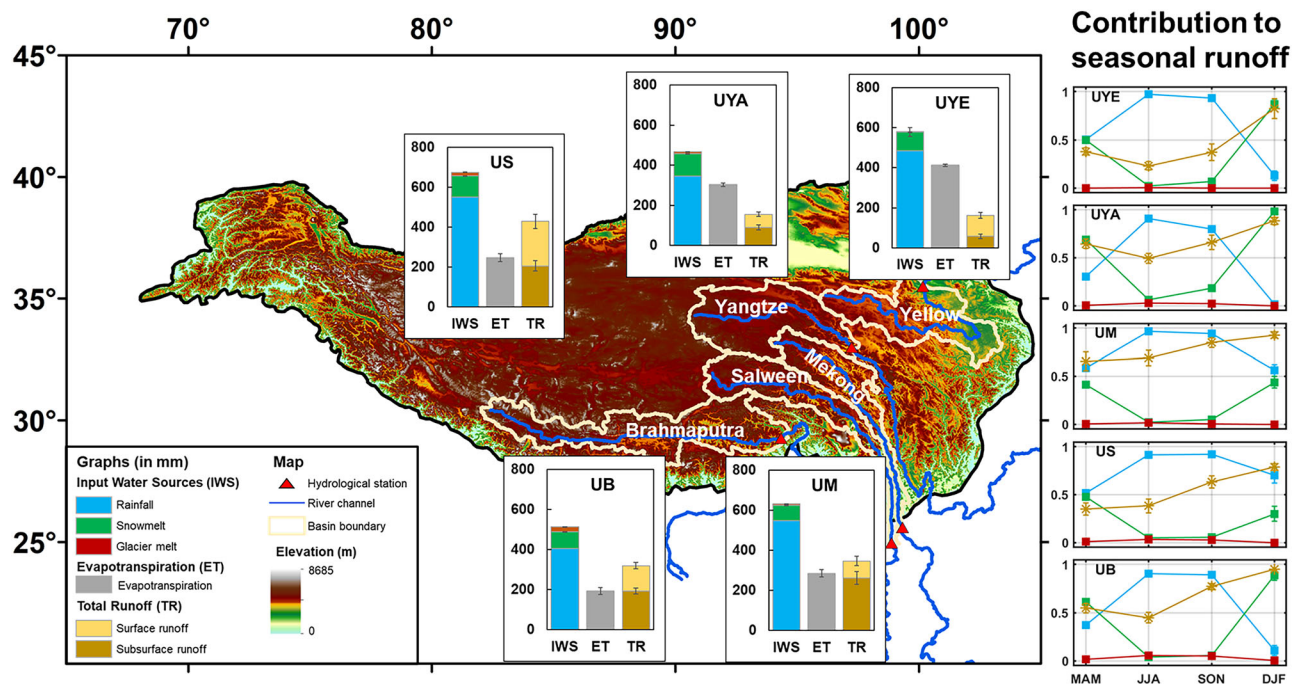


Fig. 1 | The simulated water apportionment in the five basins. UB, UM, US, UYA, and UYE refer to Upper Brahmaputra, Mekong, Salween, Yangtze, and Yellow basins. In the map, for each basin, the first column represents the input water sources (IWS), including rainfall, snowmelt, and glacier melt. The second and third columns represent the water output, which is divided into evapotranspiration (ET) and total runoff (TR). The total runoff is further divided into two components (i.e., surface runoff and groundwater runoff) based on the runoff generation pathway. The amounts of water component are quantified in millimeters (mm) in each subfigure. The error bars denote the standard deviation of the corresponding component produced by the behavioral parameter sets. The sum of the three components of input water sources equals the sum of the evapotranspiration and the two

components based on the runoff generation pathway definition (i.e., $IWS = ET + TR$). The right subplot is the simulated seasonal contribution of each runoff component for the simulated period. MAM, JJA, SON, and DJF represent spring (March, April, and May), summer (June, July, and August), autumn (September, October, and November), and winter (December, January, and February), respectively. Squares and asterisks represent the runoff components based on water source and runoff pathway definitions, respectively. For the runoff pathway definition, only the contribution of groundwater is presented because there are only two components, and their sum equals 100%. The error bars represent the standard deviation of the contribution produced by the behavioral parameter sets.

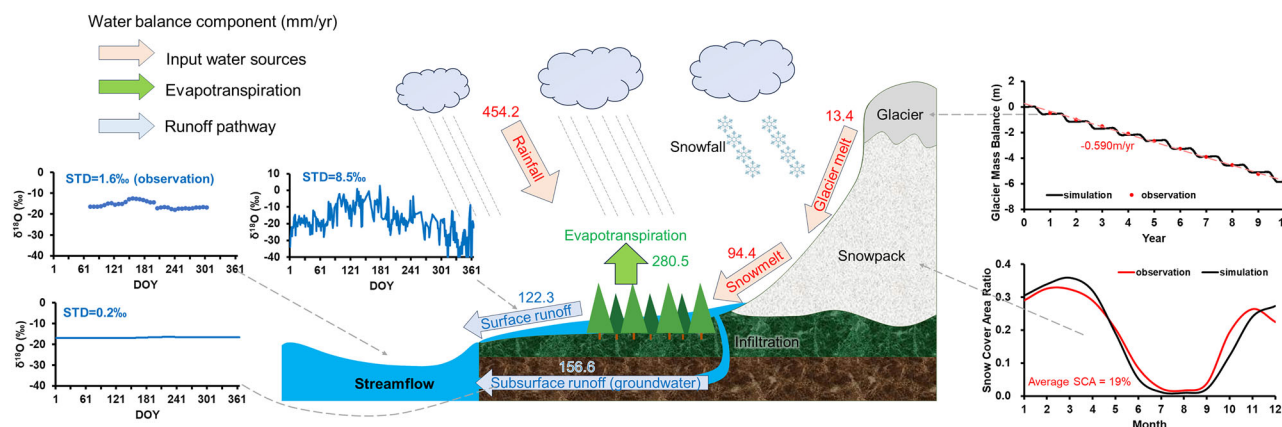


Fig. 2 | The diagram of detailed water cycle components in the major river basins on the Tibetan Plateau. The values represent the average of water components across the five basins for the simulation period. Glacier simulations are validated using glacier mass balance data, while snow simulations are validated with snow cover area ratio data, as illustrated in the two subplots on the right. Groundwater

simulations are validated using isotope data, as illustrated in the subplot on the left. The surface runoff and groundwater have different isotopic variation, represented by the standard deviation (STD). These two components must be combined in an appropriate proportion to ensure that the isotopic variation of their mixture (i.e., streamflow) matches the observations.

all five basins, this varies from basin to basin. Glacial melt contributions were largest in the Upper Brahmaputra basin ($4.8 \pm 0.2\%$), followed by the Upper Salween ($2.6 \pm 0.1\%$) and Upper Yangtze basins ($2.3 \pm 0.1\%$), and the lowest contributions are in the Upper Mekong ($0.9 \pm 0.1\%$) and Upper Yellow basins ($0.2 \pm 0.1\%$). The secondary finding is that the partitioning of runoff pathways varies largely among the five basins, with groundwater contributing 35–75% to the total runoff. From highest to lowest, the contributions are as follows: Upper Mekong ($75.4 \pm 7.2\%$), Upper Brahmaputra ($60.1 \pm 4.0\%$), Upper Yangtze ($58.3 \pm 4.0\%$), Upper Salween ($48.2 \pm 7.0\%$), and Upper Yellow ($35.2 \pm 5.4\%$). The generally high contribution of groundwater is consistent with the finding that groundwater discharges likely generate most of streamflow at most times in most rivers as reviewed by Jasechko (2018)²⁴ and that majority of global river flow are sustained by groundwater ($59 \pm 7\%$) as estimated by Xie et al.²⁵. The highest and lowest contributions of groundwater runoff in Upper Mekong and Upper Yellow basins are consistent with previous studies although the values are significantly different^{3,13}.

The seasonal variations of the proportional contribution of each component are generally similar (Fig. 1). In all five basins, rainfall is the dominant water source during summer and autumn, contributing $>80\%$ to the input water. The contribution of glacier meltwater is relatively high during summer and autumn (0.1 – 5.7%), which is close to its proportion in the annual input water (0.2 – 4.8% , Fig. 1). Both rainfall and snowmelt contribute about half of the input water during spring. The partitioning of water sources in winter depends largely on the climate conditions of each basin. In the two relatively warmer and wetter basins (Upper Salween and Mekong), rainfall accounts for more than half of the input water during winter, while the snowmelt dominates the winter runoff in the other three basins (Upper Brahmaputra, Yangtze, and Yellow), with contributions higher than 80% . The seasonal pattern of the contribution of groundwater is also related to the climate conditions. In the two warmer and wetter basins, the proportion of groundwater is lowest during spring, while for the other three basins, its lowest contribution occurs in summer. In all five basins, the winter runoff is dominated by the groundwater flow, with a contribution higher than 80% .

Although the contribution of glacier meltwater in the annual runoff is small in all the five basins at the basin scale, for the subbasin scale ($\sim 1000 \text{ km}^2$) in each of the study watersheds, the spatial variation is highly variable and correlated—not surprisingly—with the local glacier cover area ratio (Fig. 3). The contribution of glacier melt is higher than 30% in some of these small sub-watersheds regions of Upper Brahmaputra, Salween and Yangtze basins. We further examine the spatial pattern of groundwater contribution within these small subbasins and its relations with four key factors: elevation, topographic gradient, precipitation, and temperature. The strongest factors with the highest r value in each basin are shown in Fig. 4. In

the three western basins with relatively higher elevation (Upper Brahmaputra, Salween, and Yangtze), the topographic gradient is the controlling factor on the runoff pathway, showing significant negative correlation with the groundwater contribution. This is somehow different from the finding by Jasechko et al.²⁶ who found that steeper watersheds in North America and Europe tend to have more contribution from groundwater. Such a difference may be partly related to topography, where the Tibetan Plateau is much steeper than the catchments previously examined in North America and Europe, and with different geological conditions. The input precipitation tends to generate runoff directly through the surface pathway in steeper areas²⁷. These results are different in the two relatively eastern and lower basins (Upper Mekong and Yellow). The precipitation amount rather than the topographic gradient shows the most significant correlation with the partitioning of the runoff pathway. The flow connectivity in the hillslope-riparian-stream system tends to establish more easily under wetter conditions, resulting in a higher contribution of surface runoff, as seen in other studies^{28,29}. Meanwhile, in regions with higher precipitation, the extent of soil saturation is generally larger, and the rainfall intensity tends to exceed infiltration capacity more frequently, leading to more surface runoff, both as saturation overland flow (runoff produced when soil moisture is saturated) and infiltration excess overland flow (runoff produced when rainfall exceeds infiltration capacity). We should acknowledge that these correlations might be the result of autocorrelation due to the model design and parameterization, but the validation through isotope measurements of at least one location within the internal part of basin (except the Upper Yellow basin) provides some degree of confidence in the results (Supplementary Table 2 and Supplementary Fig. 8).

The value of a multi-factor dataset in model calibration

We use multiple datasets for model calibration, which help reduce the model uncertainties significantly, improving our estimations on the runoff components' contribution compared to previous work. The calibrated model performs well at simultaneously simulating the variation of streamflow, snow cover area, glacier mass balance, and stream water isotope composition (Supplementary Fig. 4, Supplementary Table 4). The average Nash-Sutcliffe efficiencies (NSE) for discharge simulation are higher than 0.8 for all five basins, which suggests that the total water volume contributing to runoff generation processes is well estimated. The seasonal fluctuation of snow cover area (Supplementary Fig. 6) and the decreasing glacier mass balance (Supplementary Fig. 7) are captured well by the model, with root mean square error (RMSE) for daily snow cover area ratio (the fraction of the basin area covered by snow) and annual average glacier mass balance (the net change in glacier mass over a year, calculated as accumulation

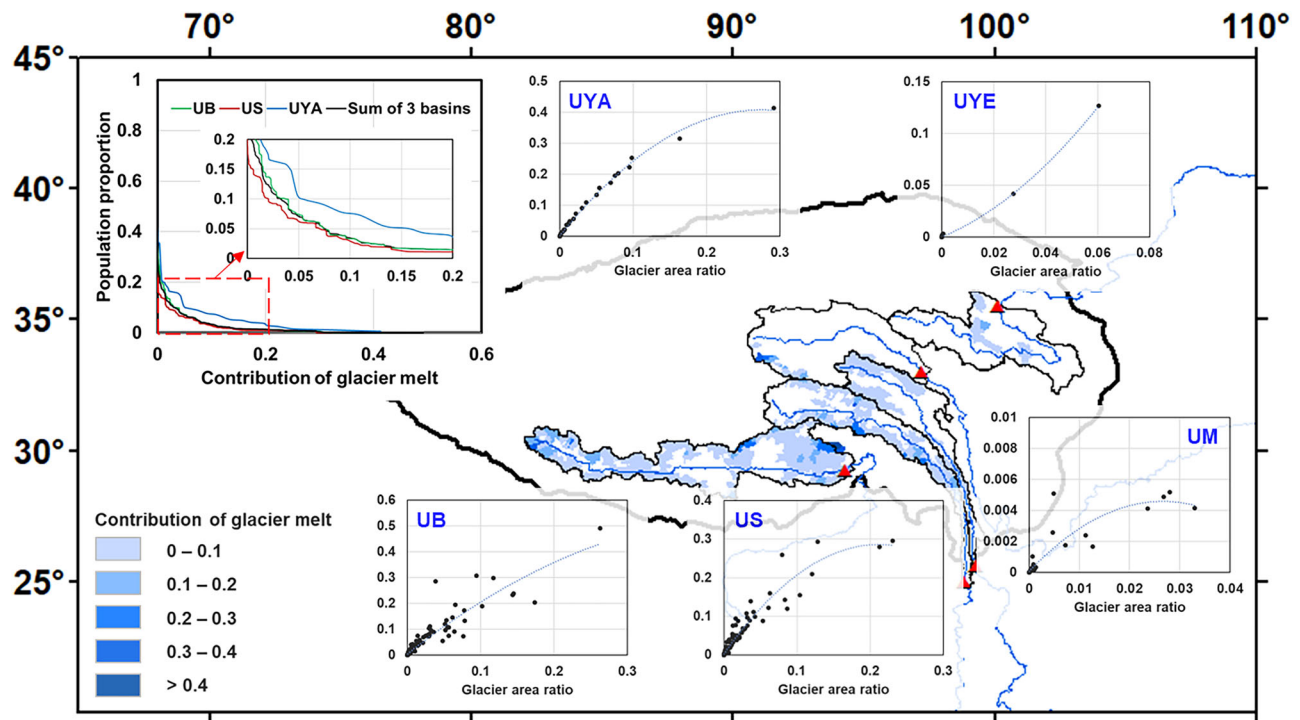


Fig. 3 | The spatial distribution of the contribution of glacier meltwater in five basins. Blue polygons represent the contribution of glacier meltwater to the total input water at the subbasin scale in each basin. The scatter plots show the relationship between the contribution of glacier meltwater and the glacier cover area ratio, each dot representing the data of a representative elementary watershed

(REW). The subplot in the top left corner shows the relation between population and the contribution of glacier melt to streamflow in the three basins with relatively higher contributions of glacier melt. It specifically shows the proportion of the population living in regions where the contribution of glacier melt exceeds a given value.

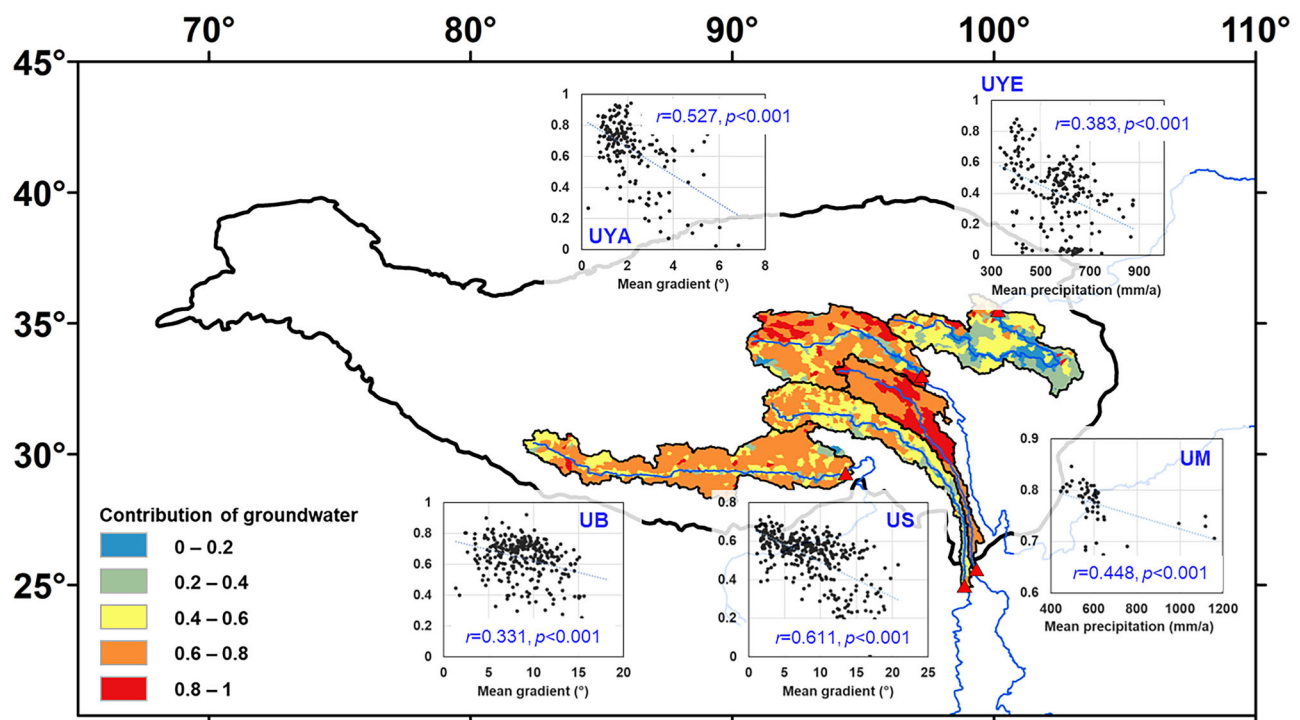


Fig. 4 | The spatial distribution and influence factors of the contribution of groundwater in five basins. Polygons with different colors represent the contribution of groundwater in the total runoff at the subbasin scale in each basin. The

scatter plots show the relationship between the contribution of groundwater and the strongest correlate (indicated by the highest r value) in each basin. The correlations are at 0.001 significance level in all five basins.

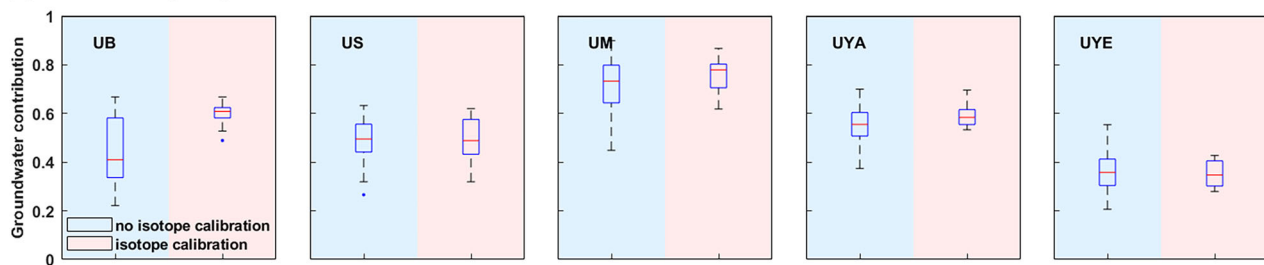
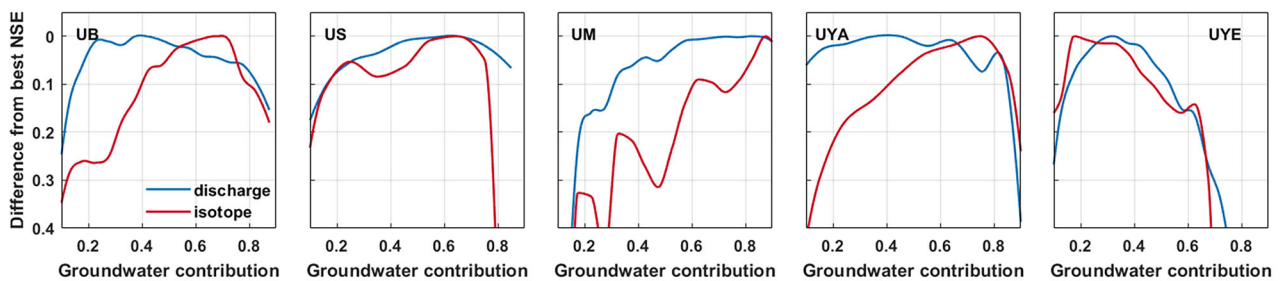
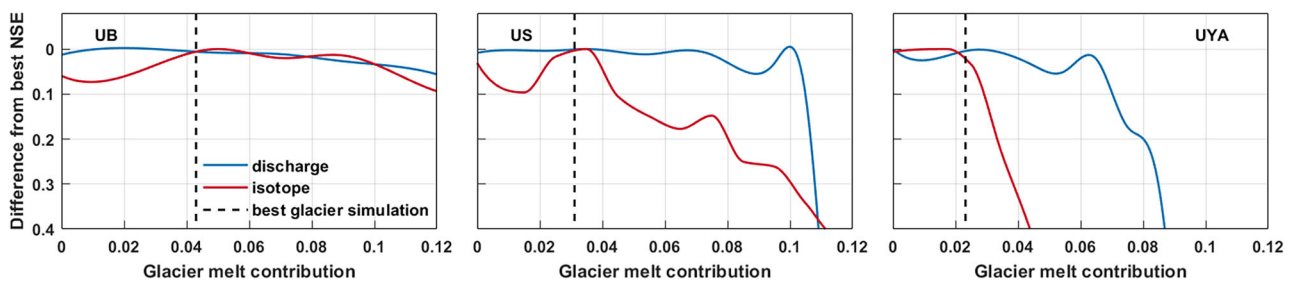
(a) Uncertainty of groundwater contribution**(b) Sensitivity to groundwater contribution****(c) Sensitivity to glacier melt contribution**

Fig. 5 | Uncertainty and sensitivity analysis. a: The contribution of groundwater obtained by different calibration scenarios. a UB, UM, US, UYA, and UYE refer to Upper Brahmaputra, Mekong, Salween, Yangtze, and Yellow basins. The boxplot represents the range (the upper and lower range line), the standard deviation (the upper and lower boundary of the box), and the mean value (the red line) of the contribution of groundwater. The boxplots in blue and red backgrounds represent the results of calibration with and without the isotope objective, respectively. **b, c** The model sensitivities to the contribution of runoff components. The lines represent the envelope curves of the scatter between model performance on streamflow/isotope

simulations and the proportion of groundwater/glacier meltwater. Blue and red curves show the performance on discharge and isotope simulations represented by the difference in NSE_{dis}/NSE_{iso} from the best metrics, respectively. The relationships between the model performance and the contribution of groundwater in all five basins are shown in subfigure **b**, while only the relationships between the model performance and the contribution of glacier meltwater in the three basins with relatively high contribution ($>2\%$) are shown in subfigure **c**. The dashed lines in subfigure **c** represent the optimal contribution of glacier melt at which the best glacier simulations are achieved.

minus ablation) of around 0.12 and 0.10 m, respectively, which constrains the cryospheric processes and the allocation among three water sources, resulting in extremely low uncertainties of contribution of water sources (mostly $\leq 0.2\%$, Figs. 1 and 2, Supplementary Table 5). The variations of stream water isotope values are reproduced well in terms of seasonality (in Upper Brahmaputra and Upper Yangtze basins), interannual variability (in Upper Yellow basin), and spatial patterns (in Upper Salween and Upper Mekong basins). The calibration towards stream water isotope data constrains the partition between different runoff pathways by utilizing different isotopic variations of runoff components with different travel times (as illustrated in Fig. 2)²⁶. The only issue for isotope simulation is the spatial pattern during the dry season that is not reproduced satisfactorily in Upper Salween and Upper Mekong basins (Supplementary Fig. 8). While this reduces confidence in these particular simulations, the isotope data during the wet season contains more information for model calibration³⁰. Overall, the fact that the model simultaneously satisfies four objectives over a long period gives confidence in the model realizations¹².

The sensitivity of streamflow and isotope simulation performances to the simulated water allocation is shown in Fig. 5b and c. The performance of the isotope simulation is more sensitive to the estimated contribution of

groundwater in all the five basins than streamflow simulation, shown in the shape of the red curves in Fig. 5b. In three of the five basins (Upper Brahmaputra, Yangtze and Yellow), the optimal proportion of groundwater contribution towards isotope simulation significantly differs from that of streamflow simulation (with difference larger than 10%). In the three basins where the contribution of glacier melt is relatively high ($>2\%$), the performance of isotope simulation is also more sensitive to the contribution of glacier meltwater than the streamflow simulation (Fig. 5c). The optimal proportion of glacier meltwater for the isotope calibration is very close to that of the glacier calibration (dashed lines in Fig. 5c), indicating that the contribution of water sources estimated by different datasets can be cross validated. The uncertainties of the contribution of groundwater obtained by calibration for the isotope objective are significantly lower than that without isotope calibration (Fig. 5a). The average standard deviation and range constrained by the isotope objective are 33% and 46% lower than the results without isotope calibration, indicating that integrating simulation and calibration of isotope into hydrological model is especially helpful for improving the confidence of surface-groundwater runoff partitioning.

Our results show the value of isotope data for increasing the model sensitivity to the simulated water allocation, reducing the equifinality, and

correcting the potential misestimated proportion of runoff components obtained by the calibration solely towards streamflow data. The value of isotope calibration for improving model performance is related to the data amount (the sampling station number and duration) and stream water sampling strategies (i.e., continuous sampling or one-time campaign sampling)^{30,31}. The benefits from isotope calibration are largest in Upper Brahmaputra and Upper Yangtze basins (as indicated by the narrower error bars in Fig. 5a), where more than 100 stream water samples were continuously collected weekly at multiple sites during wet seasons, which capture both seasonality and spatial pattern of the isotope signal. Such benefits are less in the Upper Yellow and Upper Salween basins, where isotope data collected by on-site monthly continuous sampling and spatially distributed campaign sampling are adopted for calibration, respectively. The smallest benefit comes to the Upper Mekong basin, where the isotope dataset contains only 14 measurements collected by campaign field sampling, which fails to capture sufficient information of isotope variation. Collecting more isotope data would be helpful for further improving the confidence of surface-groundwater runoff partitioning in the Upper Yellow, Salween, and Mekong basins.

Our results show much lower glacier meltwater contributions than most of the previous studies, and significant divergence also exists in the runoff component contribution estimation studies. This can be attributed to the following factors: (1) the definition of runoff components, (2) the method or model structure used to estimate the contribution of runoff components, and (3) the data used to validate the estimation result. Examining some of these studies in more detail, we illustrate these three factors' influence. For example, Lutz et al.³ established a raster-based cryospheric-hydrological model and estimated the contribution of glacier melt to runoff as 15.9% and 8.3% in Upper Brahmaputra and Upper Salween basins, significantly higher than our results (4.8% and 2.6% in Upper Brahmaputra and Upper Salween, respectively). The high contribution of glacier melt may be a result of the scarce streamflow data used for model validation in this region (the stations are all located on the western Tibetan Plateau), and the fact that no dataset related to glacier mass/area was used to validate the model performance on glacier simulation. Chen et al.⁷ estimated the contribution of glacier melt to runoff as 9.9% in the Upper Brahmaputra basin, which is almost twice as large as our finding. The difference can be attributed to the different definitions and calculation methods for the runoff components. The model adopted by Chen et al. considered the runoff as the sum of three water sources minus the change in stored water. The proportion of glacier melt was then calculated by dividing the amount of glacier meltwater by the total runoff (rather than the total input water), resulting in a higher proportion due to the smaller denominator than used in our study. If we calculate this proportion in the same way, it would be 7.6%, very close to the result of Chen et al.⁷, because datasets reflecting the glacier mass balance (glacier elevation change data or total water storage data) are used in both of the studies. A recent study conducted in the Upper Brahmaputra basin by Wang et al.⁸ adopted glacier area data of four periods as input data, and estimated similar contribution of glacier melt (3.5%) as our study⁸. However, the contribution of snowmelt was much higher (22.3%), because no dataset related to snow was used to constrain the model.

The contribution of groundwater is rather difficult to constrain by streamflow observation data in studies based on hydrological models. Specifically, calibration procedures for streamflow data tend to overestimate the contribution of direct surface runoff to achieve a good model fit^{3,8,32}. This is because most hydrological models focus more on the surface runoff generation, and are rather simplified in the simulations of infiltration and groundwater outflow processes. On the contrary, the land surface models are usually integrated with detailed simulation on groundwater processes, but the uncertainty could be rather large if the calibration procedure is not constrained by measurement data related to groundwater¹³. Our results indicate that calibration based on isotope data is an effective way to constrain the surface-groundwater runoff partitioning, by utilizing the difference in isotopic variation of components with different travel time: the

isotope signature of surface runoff is close to the precipitation input, while that of groundwater is significantly lagged and damped.

The end-member mixing method based on tracer data is another commonly used method to estimate the contribution of runoff components^{33–35}, but is rarely applied in large basins due to the strict assumptions and the poor applicability on a large scale. Boral and Sen (2020) applied this method in the large basins of the Tibetan Plateau and found that the contribution of glacier melt to runoff is around 30% in the Upper Brahmaputra basin, and even higher than 50% in the US, Upper Mekong, and Upper Yellow basins⁶. We attribute their overestimation to the point scale isotope data used for their calculations, which cannot reflect the spatial and temporal variation of isotope composition in each component, leading to very large uncertainties and biases. Our ability to determine the difference in isotope inputs in space and time allowed distinguishing the runoff components and with different travel times, which is the reason why calibration towards the isotope dataset can make the model more sensitive to the contribution of runoff pathways.

Based on the above analysis, we suggest that a clear and uniform definition of runoff components should be clarified first when discussing their contributions, to make the results comparable among relevant studies. When the hydrological modeling method is adopted to analyze this issue, modules representing the critical processes, including snow and glacier evolution, should be integrated within the model, and using multi-factor datasets related to these processes to verify the model performance is what we would deem essential. Utilization of tracer data is especially helpful to improve the model confidence by providing additional information and cross-validating the results estimated by the datasets related to water amount. Benefiting from the state-of-the-art model validated by multiple datasets, our study has the potential to establish a “reference value” of the runoff component contributions in the major rivers on the Tibetan Plateau.

Discussion

Our new model is constrained by multi-factor observation data and estimates much lower contributions of glacier meltwater to annual runoff than most previous estimations. Our work produces results that contrast with most previous studies reporting a large contribution of glacier melt, but aligns with some recent studies, such as the report on water, ice, society, and ecosystems in the Hindu Kush Himalaya, recently released by the International Center for Integrated Mountain Development^{32,36}. Despite the temporal variation of runoff components, the contribution of glacier meltwater is still extremely small in winter (Fig. 2), which is different from the previous impression that glacial meltwater provides important water sources for dry-season flows^{37–39}. This is because the Tibetan Plateau has the characteristic of concurrent rain and heat, due mainly to its monsoon climate. Our systematic estimation of the surface-groundwater runoff partitioning in the major rivers on the Tibetan Plateau indicates that groundwater is the dominant runoff contributor during the dry season. Specifically, the average glacier melt during winter in five basins is only 0.003 mm, five orders of magnitude lower than the streamflow amount in the same period (~26 mm), 87.8% of which is contributed by groundwater. The isotope simulation lends confidence to our partitioning between surface runoff and groundwater, indicating a likely underestimated contribution of baseflow by some important publications^{3,8}. The substantial contribution from groundwater is also consistent with some studies highlighting the importance of groundwater for streamflow in Himalayan rivers^{40,41}.

The contribution of glacier meltwater to runoff exhibits significant spatial variability, highly related to the glacier coverage. In terms of the role of meltwater from the viewpoint of water resources, the interaction between meltwater and the coupled human-natural system needs to be considered³⁷. The glacier melt is the dominant water source only in the headwater regions with large glacier coverage, which are generally characterized by low population density and consequently low human water demand. If we quantify the spatial distribution of subbasin scale population (population data source: Kilometer grid dataset of China's historical population spatial distribution (1990–2015), <https://doi.org/10.12078/2017121101>) and the

contribution of glacier melt to local runoff for the Upper Brahmaputra, Salween and Yangtze basins (Fig. 3), we observe an inverse relation between population and glacier melt runoff ratio (Fig. 3). Only 3% of the population (~100 thousand people) live in these three basins, in the regions where glacier melt contributes more than 10% of runoff. Whilst more than 90% people (~3 million people) live in the watershed regions with glacier melt contributions lower than 3%. Consequently, for most regions with high water demand, the change of water resources in the future will be much more dependent on the trend of precipitation inputs, rather than glacier melt. The potential significant decrease in water resource due to glacier shrinkage in a warming future is not a water resources management problem for the Tibetan Plateau that should raise public worries.

The limited contribution of glacier melt to runoff is likely a common phenomenon in most large basins worldwide. On a global scale, the average glacier loss rate over the past 20 years is around 0.52 m/yr¹⁸. Considering that the glacier area (~706,000 km²) covers around 0.47% of the global land surface area, the resulting meltwater contributes only about 2.4 mm/yr to runoff—significantly lower than the annual precipitation. This aligns with a recent perspective Gascoin (2023)⁴² who emphasized the need for an accurate representation of glaciers as water resources. However, it is important to clarify that our statement is made from a large-scale water resource perspective. Glaciers remain undeniably crucial for local water supplies in certain regions (e.g., the upper Indus River, which has significant glacier coverage⁴³) and for earth system and ecosystem sustainability. Moreover, in regions where precipitation and heat are asynchronous—unlike the concurrent rain and heat conditions in the Tibetan Plateau—such as the Pamir Mountains and pan-Arctic regions, meltwater can contribute significantly, particularly during dry seasons^{44,45}.

In summary, our work develops a new tracer-aided glacio-hydrological model to simulate the hydrological, cryospheric, and tracer processes of the five major rivers on the Tibetan Plateau. We use multi-factor datasets including streamflow, snow cover area, glacier elevation change, and stream water isotope to calibrate the model to ensure a reasonable representation of the multiple processes. Our results show that the contribution of glacier melt to the annual runoff is less than 5% in all five basins—much less than previous estimates. This indicates that the large amount of water stored as ice on the Tibetan Plateau has little contribution to the streamflow, and the runoff change would consequently be more related to the precipitation. In terms of sustaining low flow in the dry season, a critical water resource, groundwater and not glacier melt appear to control more than 80% of these dry season flows, which also contributes 35%–75% of the annual runoff. Although the contribution of glacier melt can be significant in some local headwater areas within the Tibetan Plateau, the population that heavily depends on it is limited in these isolated, upstream areas. So, the potential significant decrease in water resources due to snow and glacier shrinkage appears not to be an issue for water security outside of the Tibetan Plateau. Our work also shows the value of tracer data for improving model performance and runoff component estimation by increasing model sensitivities and reducing uncertainties, which have consequences for parameterizations of existing models that are used to predict the impact of climate change on the provisioning of water resources for human and ecosystem use. Our findings stimulate new considerations for conceptualizing hydrologic processes in the Tibetan Plateau and other mountain headwaters around the world.

Methods

Tracer-aided glacio-hydrological model

We use a semi-distributed tracer-aided glacio-hydrological model (Tsinghua Representative Elementary Watershed-Tracer aided version, THREW-T) to simulate the hydrological and cryospheric processes of the study region. The simulation period varies among basins—from 9 to 15 years—depending on data availability. (Supplementary Table 2). The THREW-T model consists of mass and energy balance equations on the Representative Elementary Watershed (REW) scale⁴⁶, and the modules of snowpack and glacier evolution are incorporated into the model to

characterize the cryospheric processes. Snow and glacier melt are simulated using a degree-day modeling approach, and a scaling equation is used to quantify the relationship between volume and area of snowpack/glacier^{43,47}. To improve the quantification of runoff component contribution, the tracer module is established to simulate the mixture and fractionation processes of environmental tracers related to the runoff and evaporation processes⁴⁷. Forced by the input data including DEM, land cover, soil, meteorological and precipitation isotope data (the detail of input data is listed in Supplementary Table 1), the model can simulate the streamflow, snow depth and cover area, glacier thickness and cover area and isotope composition of different water bodies in each REW at a daily step. Considering the difficulties in long-term precipitation sampling work with high frequency and spatial resolution within a large region, we use the output of isotopic general circulation models (iGCM) merged with in-situ measurement precipitation isotope data to force the model, which has been proved as a feasible way to establish tracer-aided hydrological model in large scale^{21,31}.

Model calibration

The model is calibrated to the multi-factor dataset including streamflow, snow cover area, glacier elevation change and stream water isotope composition. Specifically, daily streamflow data is collected from the control hydrological stations of each basin; snow cover area fraction over the whole basin is extracted from the long-term daily 5-km snow cover extent dataset over the Tibetan Plateau¹⁷; average glacier mass balance over the glacier cover areas within each basin is calculated from the yearly 0.5° gridded glacier elevation change dataset¹⁸; stream water isotope dataset is integrated by collecting data from several published articles (Supplementary Table 2). The simulated streamflow/snow/glacier/isotope characteristics are compared against the corresponding datasets to calibrate the THREW-T model. The parameters controlling the processes, including runoff generation, runoff confluence, and snow and ice melting, are determined by the calibration (Supplementary Table 3). We adopt a multi-objective optimization approach, Python Surrogate Optimization Toolbox (pySOT), to automatically calibrate the model⁴⁸. The pySOT algorithm uses radial basis functions (RBFs) as surrogate models to approximate the simulations, reducing the time for each model run. For each basin, the pySOT algorithm is repeated 100 times, and the model runs 3000 times within each pySOT program. 100 final parameter sets are obtained, among which behavioral parameter sets are selected according to the performance metric thresholds to quantify the model uncertainty³¹. The intermediate parameter sets obtained in the process of calibration are also recorded to analyze the model sensitivity.

Quantification of runoff component contribution

This study quantifies the contributions of runoff components based on two definitions as reviewed by He et al.⁹. The first definition is based on the individual water sources in the total water input triggering runoff processes, including rainfall, snowmelt, and glacier melt⁴⁹. The subsequent water movement and mixing processes of each water source is ignored in this definition. The second definition is based on the pathway of runoff-generation processes, including surface runoff and groundwater flow⁵⁰. Surface runoff consists of runoff triggered by rainfall and meltwater that feed streamflow through surface paths (e.g., saturated area, glacier cover area, and river channel). The proportional contributions of components are calculated in parallel based on the two definitions according to:

$$C_i^S = \frac{Q_i^S}{Q_{RF}^S + Q_{SM}^S + Q_{GM}^S} \quad (1)$$

$$C_j^P = \frac{Q_j^P}{Q_{SUR}^P + Q_{GW}^P} \quad (2)$$

where $C_i^S(C_j^P)$ represents the proportional contribution of runoff component $i(j)$ based on the water source (runoff pathway) definition. Subscripts

RF, SM, GM, SUR and GW represent rainfall, snowmelt, glacier melt, surface runoff, and groundwater runoff, respectively. The sum of two runoff components in the runoff pathway definition (Q_{SUR}^P and Q_{GW}^P) equals the total runoff, smaller than the sum of three runoff components in the water source definition (Q_{RF}^S , Q_{SM}^S and Q_{GM}^S) due to the evaporation loss.

Data availability

The detailed sources of datasets used in this study are provided in the Supplementary Information.

Code availability

The hydrological model used to generate the results reported in this study is available from the corresponding author upon request.

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Author contributions

Y.N. and F.T. conceived the idea. Y.N. established the model and calculated the results. Y.N., F.T., and J.M. analyzed the results. G.N., L.T., Z.L., D.Y., X.X., and T.W. provided support on the data for model calibration. S.H. and K.L. provided support on the model calibration program. Y.N. and J.M. wrote the main manuscript text. All authors reviewed the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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