Geophysical Research Letters

RESEARCH LETTER
10.1029/2020GL092354

Role of Groundwater in Sustaining Northern Himalayan Rivers

Yingying Yao1, Chunmiao Zheng2, Charles B. Andrews2, Bridget R. Scanlon3, Xingxing Kuang2, Zhenzhong Zeng1, Su-Jong Jeong4, Michele Lancia1, Yiping Wu1 and Guoshuai Li5

1Department of Earth and Environmental Science, School of Human Settlements and Civil Engineering, Xi’an Jiaotong University, Xi’an, China, 2State Environmental Protection Key Laboratory of Integrated Surface Water-Groundwater Pollution Control, School of Environmental Science and Engineering, Southern University of Science and Technology, Shenzhen, China, 3Bureau of Economic Geology, Jackson School of Geosciences, University of Texas at Austin, Austin, TX, USA, 4Department of Environmental Planning, Graduate School of Environmental Studies, Seoul National University, Seoul, Korea, 5National Tibetan Plateau Data Center, State Key Laboratory of Tibetan Plateau Earth System Sciences (LATPES), Institute of Tibetan Plateau Research, Chinese Academy of Sciences, Beijing, China

Abstract The Himalayas are critical for supplying water for ~2 billion people who live downstream, and available water is highly sensitive to climate change. The role of the groundwater system in sustaining the northern Himalayan rivers remains unknown, and this compromises Asia’s future water sustainability.

Here, we quantify the spatiotemporal contribution of groundwater to river flows in the Yarlung Zangbo Basin (upper reaches of Brahmaputra). Our results show that the groundwater recharge represents ~23% of mean annual precipitation, translating into ~30 km³/yr of baseflow, which contributes ~55% of the total river discharge in the upstream reaches and ~27% in the downstream reaches. The percentage of groundwater contribution is inversely related to topographic steepness and total precipitation, with the steepest topography and highest precipitation in the eastern Himalayas. This study fills a knowledge gap on groundwater in the Himalayas and is a foundation for projecting water changes under climatic warming.

Plain Language Summary Major rivers flowing from the Himalayan Plateau provide critical water resources for 2 billion people who live downstream and rely on Himalayan rivers for water supply, irrigation, hydropower and in-stream flows for aquatic habitat. While groundwater discharge to rivers is known to contribute to available water resources, how much Himalayan rivers depend on groundwater is poorly known. This study models the spatial groundwater flow and discharge volume to the Yarlung Zangbo, the largest river of the Himalayas in China, based on long-term climate and streamflow observations. We map the patterns of groundwater flow paths, water table elevations, recharge, and discharge to rivers. We estimate that ~55% of the total river discharge in the upstream reaches in the central Himalayas is sustained by groundwater and ~27% in the downstream reaches in the eastern Himalayas. Groundwater aquifer recharge totals at least ~9 km³ during the monsoon season (May–October) and this sustains river low flows during dry season (November–April). This study fills a knowledge gap on subsurface flow processes in the northern Himalayas and provides a baseline for comparing changes in the stream water flow under climatic warming over vulnerable mountainous headwater regions.

1. Introduction

Mountains and highlands serve as “water towers” as they provide downstream alluvial plains and lowlands with freshwater (Viviroli & Weingartner, 2008). The Himalayas are the source of water for all of the major rivers in southeast Asia and play a significant role in supplying freshwater for the vast lowland areas of China, India, Bhutan, Nepal and Pakistan (Bookhagen, 2012; Fan et al., 2019). These Himalayan “water towers” are closely related to human welfare and ecosystem health because of their role in generating runoff, groundwater recharge, providing flow to the lowlands through river networks and aquifers, transporting nutrients from porous media to the rivers which affects the biological cycle (Connolly et al., 2020), and sustaining both natural terrestrial and aquatic habitats (i.e., forests and lakes) and artificial infrastructure...
(i.e., reservoirs and hydropower stations, Immerzeel et al., 2020; Liniger & Weingartner, 1998). Thus, understanding the mechanisms of river flow generation and contribution of hydrologic components across the Himalaya is of great importance.

Mountainous groundwater systems play a critical role in sustaining river flows during the winter dry seasons, and storing rainfall in the monsoon seasons (late May–September) buffering peak river discharges (Cuthbert et al., 2019). It is estimated that the contribution of groundwater to Southern Himalayans rivers is larger than that from snow and glacier meltwater (Bookhagen, 2012), while groundwater serves as only source during the winter and provides 40% of annual discharges for river discharge in the Pamir Mountains (Pohl et al., 2015). Furthermore, groundwater systems have more far-reaching impacts on ecohydrological processes. Thawing permafrost under climatic warming can increase infiltration to the water table and facilitate vegetation growth (Young et al., 2020), but also can lead to vegetation degradation due to declining water tables (Jin et al., 2020). Previous studies on the role of Himalayans groundwater were based on hydrological separation or water balance models (Andermann et al., 2012; Schmidt et al., 2020), and the spatial groundwater flow patterns, the magnitude and seasonal distribution of groundwater recharge and discharge to rivers in Himalayan region and the factors that control these distributions are poorly understood.

To answer these questions, we characterize and evaluate how groundwater sustains the largest and longest Himalayan river in China—the Yarlung Zangbo (YZ), which covers an area of 240,000 km² and represents the upper reaches of the Brahmaputra. We use a numerical groundwater model parameterized with hydrogeological interpretations and 50 years of meteorological and streamflow records. While recent studies have explored the snow and glacier meltwater and surface runoff in YZ basin and the importance of groundwater system for mountainous regions (Biemans et al., 2019; Xu et al., 2019; Yao et al., 2010), the recharge-discharge process and contribution of groundwater to river discharge has yet to be quantified. This critical but missing information is necessary for projecting future water availability as well as changes in ecohydrological systems of Himalayas.

### 2. Description of Study Area

The YZ Basin includes the entire Himalayan range within China that is adjacent to the Tibetan Plateau (Figures 1a and 1b). The total length of the mainstream of the YZ within China is over 2,000 km. The YZ basin includes seven subbasins: Lazi and Nugesha subbasins in the upstream portion of the basin, the Shigatse, Lhasa and Yangcun subbasins in the middle portion of the basin, and the Gengzhang and Nuxia subbasins in the lower portion of the basin. The geologic setting includes the Himalayan collisional and post-collisional phases of the Indian and Eurasian Plates. Major geologic structures, from south to north, include the Tethyan Terranes, Great Counter Thrust (Yarlung suture zone) and Lhasa terranes (Hodges, 2000; Leloup et al., 2010; Zhu et al., 2011, Figure S4). Alpine permafrost and predominantly continuous permafrost are distributed along the southern and northern mountain ridge areas, with seasonally frozen ground occurring along the river valleys in between the mountain ridges (Figure 1c).

### 3. Methods

#### 3.1. Climate and Hydrological Data

We consolidated climate data from 10 stations, including daily precipitation, potential evaporation, air and ground temperature for the period 1956 through 2016 from the National Meteorological Information Center (https://data.cma.cn/) to identify the annual and seasonal climate variation (Figure S2). Since the meteorological stations are all located below an elevation of 4,500 m, the national monthly gridded precipitation product (0.25°grid spacing, Shen & Xiong, 2016) was used to validate the interpolated precipitation. Streamflow data between 1956 and 2010 from 13 gauging stations along the main stream and major branches in seven subbasins were collected for analysis.

#### 3.2. Baseflow Estimates

The algorithm of Eckhardt (Eckhardt, 2005) was employed to separate monthly the baseflow (groundwater component of streamflow) from streamflow, as it appropriately characterizes groundwater discharge...
in the recession phase following the monsoon season. Furthermore, the simulated baseflow from GLDAS Catchment Land Surface Model (CLSM) ensemble outputs (V2.0 qsb_tavg outputs) and GLDAS Noah Land Surface Model ensemble output (V2.0 qsb_acc outputs, Rodell et al., 2004) were used as independent base-flow estimates.

3.3. Groundwater Model

The ground layer which contains seasonal ice is regarded as an “aquitard” during winter frozen period, while it turns into an “aquifer” during the summer thaw period (Evans et al., 2015; Walvoord et al., 2012). Combining lithology and permafrost, we defined eight major hydrogeology-permafrost units for the YZ basin, as shown in Figure S6. Since the YZ basin is between the Himalayas and the Tibetan Plateau, the northern and southern boundary, excluding the outlet, can be regarded as no-flow boundaries. The southeastern outlet boundary is represented such that the flux is proportional to the difference between groundwater head and surface elevations outside of the model domain.

The numerical groundwater model was developed using MODFLOW-NWT (Niswonger et al., 2011), which allows wetting and drying of model cells to stabilize the numerical solution in steep topographic systems. A finite-difference grid with 201 rows and 744 columns was used with a cell size of 2 x 2 km (Figure S7). The model was vertically discretized into 12 layers, the total thickness of model was about 6.8 km. A steady state model was developed to simulate groundwater pattern during the winter-dry period (November–April). This winter-dry steady state model specifies the seasonal frozen aquifers as “aquitards” with an average hydraulic conductivity of 8 x 10^{-10} m/s. The predominantly continuous permafrost component was conceptualized as a continuous “aquifer” with an equivalent hydraulic conductivity of 5.2 x 10^{-11} m/s. The alpine permafrost component was conceptualized as a slightly more discontinuous “aquitard” than the northern continuous permafrost with an equivalent hydraulic conductivity of 7 x 10^{-11} m/s (Figure S8). The initial
estimates of groundwater recharge and hydraulic conductivity were adjusted through manual calibration and the inverse algorithm of PEST (Doherty & Hunt, 2010). The winter-dry streamflow records (November–April) were used as calibration targets for model calibration.

To evaluate the annual and seasonal contributions of groundwater discharge to total river flow, we developed multiple transient models between May and October with daily time steps. We assume that the seasonally frozen ground in the river valleys zone thaws during the summer-wet period and has a hydraulic conductivity of $3.4 \times 10^{-4}$ m/s, and the other thaw areas outside of the river valleys have a hydraulic conductivity of $8 \times 10^{-6}$ m/s. The monthly baseflow for seven subbasins computed by the digital filter method were used as targets for transient model calibration.

4. Results and Discussion

4.1. Groundwater Flow Patterns

Rainfall, snow and glacier meltwater, and groundwater discharge are the main sources of river discharge (Andermann et al., 2012). However, snow and glacier meltwater contribute to river discharge mostly during the summer months (May–October), and less during winter dry months (November–April). As the glaciers are in the lower portion of the basin, glacial meltwater is only significant in the lower stream. Given winter precipitation is predominantly snow and low in amount (<10 mm/month), we assume surface runoff is negligible and groundwater is the primary source to stream water (Hayashi, 2020). Thus, groundwater can be regarded as the primary source of river flow during the winter for most areas of YZ basin. Observed streamflow data during this period provide the best estimates of stream baseflow that is derived from groundwater discharge (Walvoord et al., 2012). The non-dimensional fit of normalized root mean square error (Fit-NRMSE, Yao et al., 2017) is 0.967 (Figure S9), and thus the model estimated baseflows are a good proxy for actual groundwater discharge to the streams.

The simulated pattern of groundwater heads and flow paths with 2 km resolution depict nested subsurface flow systems (a local scale system with short flow distances, a catchment scale flow system and a regional scale system with long flow paths) as shown in Figure 2a. Groundwater heads in the northern and southern mountainous regions, which comprise approximately 72% of the YZ, are greater than 4,000 m. Short (<5 km) and intermediate (10–50 km) distance flow paths (over 75% of total path lines) are perpendicular to the topography representing the general subsurface flow pattern. The long (>100 km) distance regional flow paths account for approximately 9% of total path lines, mainly distributed in upper stream reaches and the northern side along the main stream. The simulated flow paths from local to regional scales show how a theoretical nested groundwater cycle is represented in real watershed (Gleeson & Manning, 2008). It also validates that the within-catchment flows dominate regional groundwater system and surface-groundwater interaction (Ameli et al., 2018; Jasechko et al., 2016).

The baseflow in the stream valley areas shows a high spatial variability from less 0.1 to over 30 million m$^3$/km/yr (expressed per unit river length), while the pattern of recharge rates generally increases from north to south from less 50--200 mm/yr (expressed per unit basin area). Recharge to the groundwater system is less 200 mm/yr in ~90% (Figure 2b) of the YZ basin. High rates of groundwater discharge to the river (>10 million m$^3$/km/yr) are centered in the areas with high recharge rates (300--500 mm/yr) that are mainly found in the alluvial fan where the the Lazi, Shigatse and Nugesha subbasins converge, and mountainous areas in the Lhasa and Gengzhang subbasin. High recharge rates (over 350 mm/yr) and discharge rates (over 5 million m$^3$/km/yr) in the Shigatse and Lhasa subbasins as they are the main population centers and cultivated regions of the YZ basin, where irrigation and reservoirs regulation result in the high recharge and discharge rates. High recharge rates (over 450 mm/yr) and discharge rates (over 10 million m$^3$/km/yr) in the Gengzhang subbasin, are the result of high annual precipitation (Figure S2).

4.2. Annual and Seasonal Groundwater Recharge and Discharge

Our numerical model fully represents the timing and magnitude of low and high baseflow in each subbasin from comparison between simulated and filtered baseflow from streamflow records (e.g., top panel in Figure 3). The comparison shows a close agreement except in the Lhasa and Nuxia subbasins (Figures 3d
and 3h) where the simulated baseflow is nearly 50% of the filtered baseflow following the monsoon season (October and November) because of reservoir regulation. The spatial average subbasin groundwater discharge ranges from 58 to 127 mm/yr in the upstream portion of the YZ Basin, providing 54%–56% of annual river discharge (i.e., Lazi and Nugesha), while annual groundwater discharge increases to 65–193 mm/yr in the middle portion of the basin, providing 23%–46% of river discharge (i.e., Shigatse, Lhasa and Yangcun), and increases to 236–247 mm/yr in the lower portion of the basin providing 26%–28% of river discharge (i.e., Gengzhang and Nuxia, Table S3). Our quantified groundwater contribution to river discharge in the upper reaches is slightly higher than the estimate (40%) for the Pamir Mountains where the groundwater also is the primary contributor to stream flow in the winter and snow and glacier meltwater serves as the main recharge to groundwater (Pohl et al., 2015, 2017). This is because of the relatively flatter topography with thicker alluvial sediment in upper YZB that provide more groundwater storage, and the higher summer precipitation in the YZ basin relative to the Pamir Mountains. Our estimation of contribution of groundwater in the upper and middle subbasins of the YZ (53.7%–55.7% of river discharge) is slightly less than that of the southern Himalayas in Nepal (66% of river discharge) (Andermann et al., 2012). This discrepancy is attributed to differences in terrain-controlled flow paths and the existence of fractured basement rocks of the southern Himalayas. In the northern Himalayas the elevation difference along river flow direction (i.e., west to east) is less than 1 km, while in the southern Himalayas the elevation difference along river flow direction (i.e., north to south) is up to 6 km, which intensifies and accelerates groundwater discharge to downgradient rivers particularly in fractured aquifers.

The recharge to the groundwater system during the winter dry period represents the water volume replenished by lateral flow from outside storage flowing into the water budget domain (e.g., bottom panel in Figure 3). Because the subbasins are regarded as non-enclosed, the magnitude of the ratio between precipitation and recharge (R/P) indicates the water receiving and yielding capacity from groundwater storage and other sources outside of its subbasin except infiltration from precipitation. This results in the minimum and maximum peak R/P ratios in the Lazi and Yangcun subbasins of 1.2 and 8.3, respectively. In general, our results show that the groundwater sustains low river flows in the winter. The groundwater discharge in

**Figure 2.** Spatial distribution of groundwater flow. (a) Simulated groundwater flow paths and heads; the color of the lines represents the distance of the flow path from source to sink area, and the frequency histograms of the distance of flow path and head are showed in the left side. (b) Simulated average annual groundwater discharge volume (Qg) in the form of baseflow along streams per kilometer and groundwater recharge (R) per unit basin area, and the frequency histograms of Qg and R are showed in the left side.
the winter-dry period of November–April is equivalent to ~37 mm of recharge on the YZ basin, accounting for ~12% of total annual river discharge for the entire YZ. The winter groundwater discharge is equivalent to 30% of annual average recharge of ~124 mm/yr over the entire watershed. Because aquifer recharge from precipitation and meltwater is minimal during the winter, winter groundwater discharge implies that ~9 km$^3$ of water is stored in aquifers in the YZ basin during the summer thaw period from precipitation, snow and glacier meltwater and irrigation.

Widely-utilized land surface models for hydrological studies in water tower regions perform poorly in the high mountain region of the YZ basin in comparison to the results of our study. For example, the baseflow outputs by GLDAS-CLSM and NOAH shows the same seasonal pattern of stream flow timing but differ in magnitude for the YZ from the results of our study. Particularly, the simulated baseflows between July and January by GLDAS-CLSM and NOAH are severely underestimated and highly overestimated, respectively (Figure S10). Earth system models lack characterization of the lateral flow patterns and flow paths for groundwater. This highlights the importance of the development of regional groundwater models to improve hydrological performances of the global earth system models by incorporating complexities of groundwater systems as a basis for projecting future water changes in the high mountain areas.
We further characterized the role of topography and recharge gradients in distributing groundwater flow and discharge in northern Himalayan mountainous areas based on simulated results (Figures 4, S11). The relief roughness is used to evaluate the steepness of the terrain (Gleeson & Manning, 2008), with lower relief roughness equating to flatter topography. The length of groundwater flow paths is correlated with relief, as the flatter the topography (lower relief roughness), the longer the flow path that is produced, and the steeper the topography is (higher relief roughness), the shorter flow path that is produced (Figure 4a). Our result directly validates the control of topography on flow path, as demonstrated by transit and residence times (McGuire et al., 2005; Tetzlaff et al., 2009). The R/P is significantly correlated with annual Qg in areas with high relief roughness (Figure 4b), however, this correlation is not significant for all flow paths. This indicates that the volume of groundwater discharge from shorter flow paths is correlated with recharge, while the volume of groundwater discharge from longer flow path is not well correlated with recharge.

Precipitation in the YZ basin increases from west to east, with the highest precipitation in the lower portion of the YZ basin where the topography is steep (Figure S11). In the lower portion of the basin, surface runoff during the monsoon period is significant reducing the percentage groundwater contribution to total river flow. This explains the decreasing trend in groundwater contribution to streamflow from upstream to downstream in the YZ basin.

**4.4. Implications**

The characteristics of groundwater flow and its recharge-discharge mechanisms are highly relevant to addressing scientific gaps on critical issues of water resources, ecohydrological processes, and cryospheric feedbacks under climatic warming in water tower regions globally. From aspect of water resources, the snow and glacier meltwater contributes 50%–70% of annual river discharge in the upstream reaches of the YZ basin (Biemans et al., 2019), while groundwater sustains winter low river flow and contributes ~55% of annual river discharge. The snow cover and glacier extent has declined in recent decades (Hock et al., 2019), and thus has resulted in decreases in annual river discharge, groundwater recharge from meltwater and discharge as baseflow. In terms of rainfall, an increase in frequency and intensity of summer extreme rainfall is projected across the Himalayan-Tibetan mountainous region, particularly in the eastern Himalayan chain (lower reaches of the YZ basin, Palazzi et al., 2013; Panday et al., 2015; Sanjay et al., 2017). Groundwater recharge and discharge would increase with increases in amount of precipitation (Figure S12 a), however...
recharge and discharge would be negatively affected by enhanced intensity rainfall altering the magnitude of annual baseflow. Thawing permafrost increases the vertical hydraulic conductivity resulting in increased groundwater recharge and discharge and in some cases declines in water table elevations (Figure S12b). Although changes in permafrost depth and extent respond slower to climatic warming than glaciers, permafrost degradation will reshape the groundwater flow and hydrological cycle over the long term (Brun et al., 2017; Forster et al., 2014; Ji et al., 2020). Moreover, the ground ice within the porous media would be an additional source of water within the groundwater system (Bense et al., 2009; Forster et al., 2014). Our evaluation fills a knowledge gap in groundwater systems for “water tower” regions and provides a basis for extending these studies.

5. Conclusions

The groundwater flow patterns and recharge-discharge mechanisms within the aquifers of the northern Himalayans are poorly known, which limits understanding of the hydrological cycle and predictions of future changes in the sensitive “water tower” mountainous regions. A three dimensional, physically based regional scale groundwater model was developed for Yarlung Zangbo basin on the northern Himalayan mountainous region. Major study findings include that the short (<5 km) and intermediate (10–50 km) distance flow paths account for over 75% and dominate spatial flow pattern for the groundwater system of the northern Himalayans in China. We estimate that ∼124 mm/yr, ∼23% of mean precipitation, recharges to groundwater, and this translates into ∼30 km$^3$/yr of baseflow. The Northern Himalayan groundwater system in China contributes 55%–27% of annual river discharge from west upstream to east downstream. The percentage groundwater contribution to river discharge is inversely related to steepness of the topography and precipitation, with the steepest topography and highest annual precipitation in the downstream reaches. Our results also indicate that the groundwater recharge and discharge would increase with projected increasing ratio of recharge to precipitation, and thawing permafrost would increase groundwater recharge and discharge. Our evaluation fills a knowledge gap in one of most complex alpine groundwater systems, and provides a baseline for extending geoscience and socio-economic studies in high mountainous regions.

Data Availability Statement

The daily climate datasets for this study are from the National Meteorological Information Center (http://data.cma.cn/en/?r=data/detail&dataCode=SURF_CLI_CHN_MUL_DAY_CES) and grid precipitation data is available through Shen and Xiong (2016). The streamflow observations were obtained from the Hydrology and Water Resources Bureau of Tibet Autonomous Region through a restricted use agreement per government regulations. Those interested in using the streamflow observation data need to follow the same procedure.

Acknowledgments

The authors thank Harihar Rajaram, Christoff Andermann and an anonymous reviewer for their comprehensive and constructive comments. We are grateful to Jeffrey McDonnell for providing valuable comments on the initial draft of the paper. We acknowledge the capable assistance from Yukun Deng and Jingyi Hu. This work is supported by the National Natural Science Foundation of China (NSFC) research program (grants nos. 91747204, 41910123, and 41861124003) and the Shenzhen Municipal Science and Technology Innovation Committee (JCYJ20160530190547253).

References

Ameli, A. A., Gabrielli, C., Morgenstern, U., & McDonnell, J. J. (2018). Groundwater subsidy from headwaters to their parent water watershed: A combined field-modeling approach. Water Resources Research, 54(7), 5110–5125. https://doi.org/10.1029/2017wr022356
Andermann, C., Longuevergne, L., Bonnet, S., Crave, A., Davy, P., & Gloaguen, R. (2012). Impact of transient groundwater storage on the discharge of Himalayan rivers. Nature Geoscience, 5(2), 127–132. https://doi.org/10.1038/ngeo1336
Bense, V. F., Ferguson, G., & Kooi, H. (2009). Evolution of shallow groundwater flow systems in areas of degrading permafrost. Geophysical Research Letters, 36(22). https://doi.org/10.1029/2009gl039225
Biemans, H., Siderius, C., Lutz, A. F., Nepal, S., Ahmad, B., Hassan, T., et al. (2019). Importance of snow and glacier meltwater for agriculture on the Indo-Gangetic Plain. Nat Sustain, 2(7), 594–601. https://doi.org/10.1038/s41893-019-0305-3
Bookhagen, B. (2012). Himalayan groundwater. Nature Geoscience, 5(2), 97–98. https://doi.org/10.1038/ngeo1366
Brookfield, M. (1993). The Himalayan passive margin from Precambrian to Cretaceous times. Sedimentary Geology, 84(1–4), 1–35. https://doi.org/10.1016/0037-0738(93)90042-4
Brun, F., Berthier, E., Wagnon, P., Kääb, A., & Treichler, D. (2017). A spatially resolved estimate of High Mountain Asia glacier mass balances from 2000 to 2016. Nature Geoscience, 10(9), 668–673. https://doi.org/10.1038/ngeo2999
Brutsaert, W. (2008). Long-term groundwater storage trends estimated from streamflow records: Climatic perspective. Water Resources Research, 44(2). https://doi.org/10.1029/2007wr006518
Carosi, R., Montomoli, C., & Iaccarino, S. (2018). 20 years of geological mapping of the metamorphic core across Central and Eastern Himalayas. Earth-Science Reviews, 177, 124–138. https://doi.org/10.1016/j.earscirev.2017.11.006
Chen, J., Huang, B., & Sun, L. (2010). New constraints to the onset of the India–Asia collision: paleomagnetic reconnaissance on the Linzizong Group in the Lhasa Block, China. Tectonophysics, 489(1–4), 189–209. https://doi.org/10.1016/j.tecto.2010.04.024
Cheng, G., & Wu, T. (2007). Responses of permafrost to climate change and their environmental significance, Qinghai-Tibet Plateau. *Journal of Geophysical Research, 112*(F2), F02S03. https://doi.org/10.1029/2006JF000631

Connolly, C. T., Cardenas, M. B., Burkart, G. A., Spencer, R. G., & McClelland, J. W. (2020). Groundwater as a major source of dissolved organic matter to Arctic coastal waters. *Nature Communications*, 11(1), 1–8. https://doi.org/10.1038/s41467-020-15250-8

Cuthbert, M. O., Gleeson, T., Moordoen, N., Befus, K. M., Schneider, A., Hartmann, J., et al. (2019). Global patterns and dynamics of climate-groundwater interactions. *Nature Climate Change*, 9(2), 137–141. https://doi.org/10.1038/s41558-018-0386-4

Dobrzycki, J. E., & Hunt, R. J. (2010). Approaches to highly parameterized inversion: A guide to using PEST for groundwater-model calibration (pp.2382–0328). US Geological Survey. https://doi.org/10.3133/2010gl05169

Eckhardt, K. (2005). How to construct recursive digital filters for baseflow separation. *Hydrological Processes*, 19(2), 507–515. https://doi.org/10.1002/hyp.5675

Evans, S. G., Ge, S., & Liang, S. (2015). Analysis of groundwater flow in mountainous, headwater catchments with permafrost. *Water Resources Research*, 51, 9564–9576. https://doi.org/10.1002/2015wr017372

Pan, Y., Clark, M., Lawrence, D. M., Swenson, S., Band, L., Bramley, S., et al. (2019). Hillslope Hydrology in global change research and earth system modeling. *Water Resources Research*, 55, 1377–1772. https://doi.org/10.1029/2018WR023903

Foglia, L., Hill, M. C., Mehl, S. W., & Burlando, P. (2009). Sensitivity analysis, calibration, and testing of a distributed hydrological model using error-based weighting and one objective function. *Water Resources Research*, 45(6), W06427. https://doi.org/10.1029/2008wr007255

Forster, R. R., Box, J. E., Van Den Broeke, M. R., Miege, C., Burgess, E. W., Van Angelen, J. H., et al. (2014). Extensive liquid meltwater storage in firm within the Greenland ice sheet. *Nature Geoscience*, 7(2), 95–98. https://doi.org/10.1038/ngeo2043

Guo, W., Liu, S., Xu, J., Wu, L., Shangguan, D., Yao, X., et al. (2017). The second Chinese glacier inventory: data, methods and results. *Geophysical Research Letters*, 44(6), 2953–2960. https://doi.org/10.1002/2017gl073604

Jasechko, S., Cardenas, M. B., Burkart, G. A., Spencer, R. G., & McClelland, J. W. (2020). Groundwater as a major source of dissolved organic matter to Arctic coastal waters. *Nature Communications*, 11(1), 1–8. https://doi.org/10.1038/s41467-020-15250-8
Pohl, E., Gloaguen, R., Andermann, C., & Knoche, M. (2017). Glacier melt buffers river runoff in the Pamir Mountains. *Water Resources Research*, 53(3), 2467–2489. https://doi.org/10.1002/2016WR019431

Pohl, E., Knoche, M., Gloaguen, R., Andermann, C., & Krause, P. (2015). Sensitivity analysis and implications for surface processes from a hydrological modelling approach in the Gunt catchment, high Pamir Mountains. *Earth Surface Dynamics*, 3(3), 333–362. https://doi.org/10.5194/esurf-3-333-2015

Pollock, D. W. (2012). *User guide for MODPATH version 6: A particle tracking model for MODFLOW*. US: US Department of the Interior, US Geological Survey. https://doi.org/10.3133/mwgs41

Ratschbacher, L., Frisch, W., Liu, G., & Chen, C. (1994). Distributed deformation in southern and western Tibet during and after the India-Asia collision. *Journal of Geophysical Research*, 99(B10), 19917–19945. https://doi.org/10.1029/94JB00932

Rodell, M., Houser, P. R., Jambor, U., Gottschalck, J., Mitchell, K., Meng, C.-J., et al. (2004). The global land data assimilation system. *Bulletin of the American Meteorological Society*, 85(3), 381–394. https://doi.org/10.1175/bams-85-3-381

Sanjay, J., Krishnan, R., Shrestha, A. B., Rajbhandari, R., & Ren, G.-Y. (2017). Downscaled climate change projections for the Hindu Kush Himalayan region using CORDEX South Asia regional climate models. *Advances in Climate Change Research*, 8(3), 185–198. https://doi.org/10.1016/j.accre.2017.08.003

Schmidt, A. H., Lüdtke, S., & Andermann, C. (2020). Multiple measures of monsoon-controlled water storage in Asia. *Earth and Planetary Science Letters*, 546, 116415. https://doi.org/10.1016/j.epsl.2020.116415

Shen, Y., & Xiong, A. (2016). Validation and comparison of a new gauge-based precipitation analysis over mainland China. *International Journal of Climatology*, 36(1), 252–265. https://doi.org/10.1002/joc.4341

Tapponnier, P., Mercier, J. L., Proust, F., Andrieux, J., Armijo, R., Bassoullet, J. P., et al. (1981). The Tibetan side of the India-Eurasia collision. *Nature*, 294(5840), 405–410. https://doi.org/10.1038/294405a0

Tetzlaff, D., Seibert, J., McGuire, K. J., Laudon, H., Burns, D. A., Dunn, S. M., et al. (2009). How does landscape structure influence catchment transit time across different geomorphic provinces? *Hydrological Processes*, 23(6), 945–953. https://doi.org/10.1002/hyp.7240

Viviroli, D., & Weingartner, R. (2008). “Water towers” — A global view of the hydrological importance of mountains. *In: Zhang, P., Najman, Y., Mei, L., Millar, I., Sobel, E. R., Carter, A., & et al. (2019). Palaeodrainage evolution of the large rivers of East Asia, and Himalayan-Tibet tectonics. *Earth-Science Reviews*, 175, 144–159. https://doi.org/10.1016/j.earscirev.2019.02.003

Walvoord, M. A., Voss, C. L., & Wellman, T. P. (2012). Influence of permafrost distribution on groundwater flow in the context of climate-driven permafrost thaw: Example from Yukon Flats Basin, Alaska, United States. *Water Resources Research*, 48(7). https://doi.org/10.1002/wrcr.20111595

Xie, J., Liu, X., Wang, X., Yang, T., Liang, K., & Liu, C. (2020). Evaluation of typical methods for baseflow separation in the contiguous United States. *Journal of Hydrology*, 583, 124628. https://doi.org/10.1016/j.jhydrol.2020.124628

Xu, R., Hu, H., Tian, F., Li, C., & Khan, M. Y. A. (2019). Projected climate change impacts on future streamflow of the Yarlung Tsangpo-Brahmaputra River. *Global and Planetary Change*, 175, 1–131. https://doi.org/10.1016/j.gloplacha.2019.01.012

Yao, T., Li, Z., Yang, W., Guo, X., Zhu, L., Kang, S., et al. (2010). Glacial distribution and mass balance in the Yarlung Zangbo River and its tributaries. *Chinese Science Bulletin*, 55(20), 2072–2078. https://doi.org/10.1007/s11434-010-3213-5

Yao, Y., Zheng, C., Andrews, C., Zheng, Y., Zhang, A., & Liu, J. (2017). What controls the partitioning between baseflow and mountain block recharge in the Qinghai-Tibet Plateau? *Geophysical Research Letters*, 44(16), 8352–8358. https://doi.org/10.1002/2017gl074344

Yin, A. (2006). Cenozoic tectonic evolution of the Himalayan orogen as constrained by along-strike variation of structural geometry, exhumation history, and foreland sedimentation. *Earth-Science Reviews*, 78(1), 1–131. https://doi.org/10.1016/j.earscirev.2005.05.004

Young, N. L., Lemieux, J. M., Delottier, H., Fortier, R., & Fortier, P. (2020). A Conceptual Model for Anticipating the Impact of Landscape Evolution on Groundwater Recharge in Degrading Permafrost Environments. *Geophysical Research Letters*, 47(11). https://doi.org/10.1029/2020GL092354

Zhang, J., Santosh, M., Wang, X., Guo, L., Yang, X., & Zhang, B. (2012). Tectonics of the northern Himalaya since the India-Asia collision. *Gondwana Research*, 21(4), 939–960. https://doi.org/10.1016/j.gr.2011.11.004

Zhang, P., Najman, Y., Mei, L., Millar, I., Sobel, E. R., Carter, A., et al. (2019). Palaeodrainage evolution of the large rivers of East Asia, and Himalayan-Tibet tectonics. *Earth-Science Reviews*, 175, 144–159. https://doi.org/10.1016/j.earscirev.2019.02.003

Zhu, D., Zhao, Z., Niu, Y., Mo, X., Chung, S., Hou, Z., et al. (2011). The Usaha Terrane: Record of a microcontinent and its histories of drift and growth. *Earth and Planetary Science Letters*, 301(1), 241–255. https://doi.org/10.1016/j.epsl.2010.11.005