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Discharge Deficits in the Nepali Himalaya Linked to Greening and Warming

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Abstract

1
2 Anthropogenic climate change and rapid infrastructure development have drastically altered the hydrology of many watersheds, influencing the speed at which water is absorbed, stored, and distributed.
3
4 In this work, we use long-term daily discharge records in the Nepali Himalaya alongside rainfall and
5 snowmelt data to explore whether there have been large-scale shifts in the conversion of upstream water
6 into discharge throughout the region. We find that for the majority of watersheds studied over decadal
7 time scales (\sim 1960s-2015), both rainfall and snowmelt are taking longer to be converted into discharge.
8 We link these changes to increasing water storage deficits, where relatively more surface water is being
9 diverted to soil moisture, vegetation uptake, and deeper water storage reservoirs. We propose that
10 large-scale climate change and vegetation greening have modified catchment-level precipitation-discharge
11 relationships in the Nepali Himalaya.

12 Introduction

13 The Himalaya have seen rapid climate changes in the past few decades, alongside extensive infrastructure
14 development as road networks penetrate deeper into remote areas. Substantial temperature increases have
15 been observed¹, alongside changes in the cryosphere^{2;3}, broad-scale land cover change and vegetation green-
16 ing^{4;5;6;7}, and shifting precipitation patterns^{8;9}. Changes in precipitation patterns, the timing and volume
17 of snowmelt, and increased water demands from drying soils and more productive vegetation are expected
18 to produce overlapping and non-linear changes in downstream discharge. New infrastructure can also drasti-
19 cally change the speed at which precipitation is converted into downstream discharge, driving both increases
20 (e.g., faster surface runoff on denuded slopes) and decreases (e.g., hydropower dams). Understanding how
21 the relationship between upstream precipitation, snowmelt runoff, and downstream discharge of Himalayan
22 watersheds is changing is of critical importance for successful and sustainable continued development.

23 A large body of recent work e.g.,^{10;11;12;13;14} has noted changes in regional snowmelt patterns, with
24 knock-on influences on discharge and discharge seasonality. In particular, warming does not always lead to
25 faster or earlier snowmelt, and there are large regional differences in the response of discharge to changes
26 in snowpack. Further, the magnitude of snowmelt and discharge changes is often uncertain¹⁵. There is
27 evidence for a direct increase in discharge due to snowmelt changes in some catchments⁷, but this is not
28 necessarily a universal relationship. In particular, widely reported global vegetation greening¹⁶, driven by
29 temperature increases and CO₂ fertilization¹⁷, is expected to increase soil-water demands, which, alongside
30 decreasing snowmelt rates in some regions¹², could change how water propagates downstream. It is thus
31 also possible that discharge may decrease in some catchments even if the snowmelt season intensifies.

32 Discharge time series encode one part of the water balance of an upstream region. If the inputs (e.g.,
33 snowmelt, rain) did not change through time, changes in discharge would be driven by modifications of
34 the characteristics of the watershed itself – for example, infiltration rate, soil-water uptake, irrigation, or
35 slowing of the river due to diversion for hydropower. In the real world, the relationship between discharge
36 and upstream water inputs is more complex, both due to the time-varying nature of inputs (e.g., storm
37 magnitude, snowmelt timing), but also variable levels of water loss due to, e.g., evapotranspiration. For
38 discharge in the Himalaya, the most salient first-order controls to examine are rainfall and snowmelt⁸;
39 changes in the relationship between inputs (rainfall, snowmelt) and outputs (discharge) can hence be used
40 to understand changes in how water moves through the landscape, and what factors control the strength
41 and direction of those relationships.

42 In this work, we leverage a dense set of discharge measurements across Nepal alongside catchment-summed
43 upstream rainfall, snowmelt, total precipitation, temperature, and evaporation time series from ERA5¹⁸

44 and vegetation data from MODIS¹⁹ to examine potential drivers of changes in downstream discharge. We
45 hypothesize that changes in temperature and precipitation have generally slowed how water is routed through
46 the landscape, with drying soils and greening vegetation absorbing more direct rainfall, increasing soil-water
47 deficits, and leading to a slower release of water into rivers. We contextualize these changes with both
48 climatic shifts and anthropogenic factors such as hydropower projects and road construction.

49 **Data and Methods**

50 **In-Situ Discharge Data**

51 We use a collection of 85 discharge stations collecting daily data from the Nepali Department of Hydrology
52 that cover the width of Nepal (Supplemental Figure S1). Data with less than 10 full years (Supplemental
53 Figure S1) are discarded from our analysis. For each station, we calculate the upstream watershed using
54 TopoToolbox²⁰; for those with unclear geographic locations (e.g., not directly located on the flow network),
55 we use the closest major stream within 1 km of the provided latitude/longitude of each station. For each
56 discharge time series, we calculate trends in annual mean discharge as well as annual high/low percentiles (5th
57 and 95th) (Supplemental Figures S2-S3). The data all follow a similar seasonal distribution (i.e., monsoonal
58 rainfall and dry winters) (Supplemental Figure S4).

59 **Climate, Environmental, and Human Impact Data**

60 For each watershed with more than 10 years of data, we extract daily-aggregated climatic data from ERA5¹⁸
61 via Google Earth Engine²¹. We sum (precipitation, snowmelt, evaporation) or average (temperature) the
62 gridded data over each watershed, yielding long-term (1950-2024) daily time series.

63 To contextualize changes in precipitation-discharge relationships, we compute two additional annual-scale
64 metrics from the climate time series: (1) a Simple Daily Intensity Index (SDII, the average precipitation on
65 wet days) and (2) the annual water balance (total precipitation minus evaporation). We further calculate
66 trends in both of these metrics to compare with trends in discharge-precipitation correlation; trends are
67 computed via linear regression, with only statistically significant ($p < 0.05$) trends included in our analysis.

68 We also use MODIS NDVI data (MOD13Q1, 2001-2024¹⁹) to compute long-term averages and trends
69 in vegetation cover. We further calculate the trend in the annual number of days above the long-term 25th
70 percentile NDVI as a proxy for total growing season length and soil-water uptake intensity.

71 We use five data sets to measure upstream modification of each watershed. (1) Human Footprint In-
72 dex data (2000-2022)²²; (2) approved and constructed Nepali hydropower infrastructure projects permitted

73 by the Department of Electricity Development (<https://doed.gov.np/>, compiled April 2025); (3) Microsoft
74 Building Footprints²³ (accessed April 2025) data for Nepal; (4) Open Street Maps tagged road networks (ac-
75 cessed April 2025)²⁴; and (5) reported landslides on the Nepali BIPAD portal²⁵ (<https://bipadportal.gov.np/>,
76 compiled April 2025), 1998-2025. Each of these data sets measures a different but overlapping aspect of wa-
77 tershed modification. It is important to note that these data sets are not used to measure the magnitude
78 of impact of each individual change, but rather the general character of each watershed. While it would
79 be useful to know the exact magnitude of each landslide and the year of construction of each building and
80 road, that data is not consistently available. In our analysis, we focus rather on correlations between changes
81 in upstream watersheds and changes in discharge-precipitation relationships. To that end, we reduce the
82 Human Footprint Index data to a simple watershed average and count the number of buildings, roads, in-
83 frastructure projects, and landslides per unit area for each watershed. As a final note, building footprints
84 and infrastructure are generally confined to Nepal, while some of the watersheds cross upstream into China;
85 to limit this influence, any watershed with more than 10% of its area in China is removed from comparisons
86 with infrastructure counts.

87 **Time Series Correlation**

88 To analyze the correlation between climatic variables and discharge, we first compute Kendall’s τ statis-
89 tics over seasonal (90-day) and inter-annual (3-year) time scales using rolling windows. This allows us to
90 understand generally how discharge responds to different forcings throughout the year, as well as the long-
91 term structure of, e.g., rainfall-discharge correlation. We further compute trends in long-term inter-annual
92 Kendall’s τ statistics to understand how the relationship between precipitation and discharge has shifted
93 through time.

94 As a second step, we use non-negative least-squares to compute the optimal lag time between rainfall and
95 snowmelt and downstream discharge. In short, we generate a set of time-shifted realizations of our input
96 (snowmelt, rainfall) time series from $n=1-90$ days and compute the best-fit non-negative linear model that
97 describes the relationship between input and discharge; we force the fits to be non-negative to maintain the
98 physically realistic constraint that rainfall and snowmelt cannot produce negative discharge. The weighted
99 average of those lag-contributions is used here as a metric of transit time, or how long it takes for, e.g.,
100 rainfall to be converted into downstream discharge. We compute this metric on a three-year rolling window
101 to assess whether or not transit times have shifted over the course of recent decades.

102 We further note that for all climate comparisons, we subset climate data to the temporal extent of each
103 individual discharge station’s data availability. This means that trends presented for each discharge station

104 do not necessarily cover the same time periods, but any comparison with contextual (e.g., climate) data is
105 done using the same temporal basis as the discharge data. We focus here on showing spatial patterns (using
106 a large number of stations) rather than focusing on the (much smaller) set of stations with several decades
107 of discharge data.

108 Results

109 Diverging Discharge and Precipitation Trends

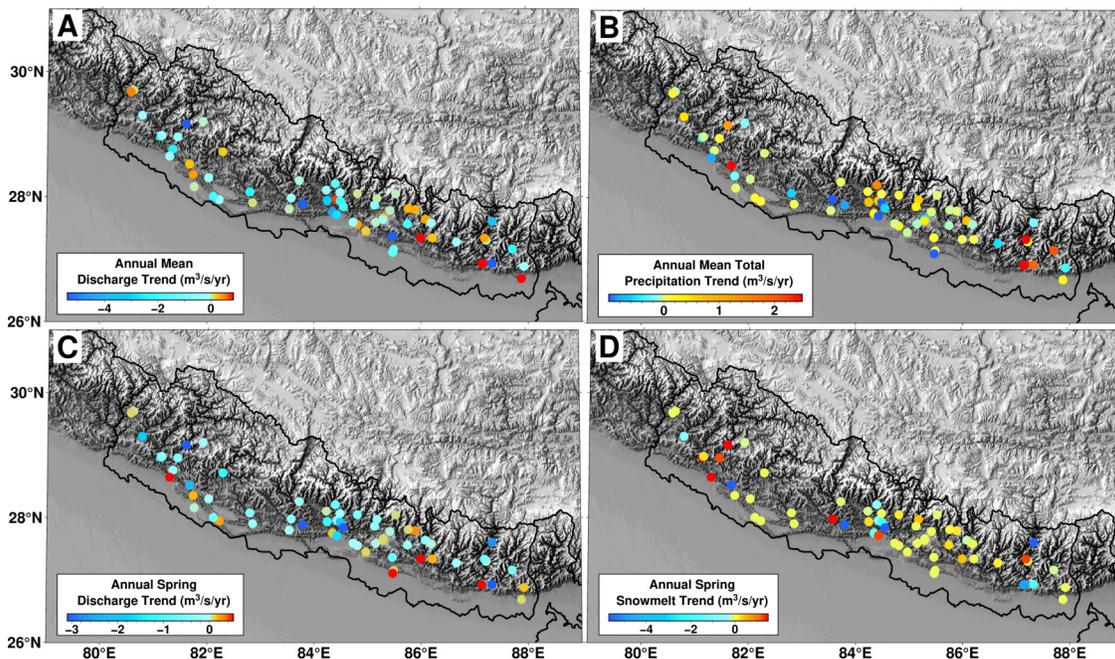


Figure 1: **Discharge and Precipitation Trends.** (A) Trends in mean annual discharge from in-situ data, and (B) trends in mean annual total precipitation from ERA5 data (converted to m^3/s equivalent)¹⁸. Total precipitation trends cover the same period as the discharge trends; see Supplemental Figure S1 for data coverage periods for all stations. (C) same as (A), but for the spring (day-of-year 100-150). (D) Spring snowmelt trend (from ERA5 data, converted to m^3/s equivalent). Discharge trends are generally negative, while total precipitation and spring snowmelt have broadly increased over the same time periods.

110 When we consider simple linear trends in both discharge and upstream water (proxied here by total
111 precipitation at the annual scale and snowmelt runoff for the spring season), we find that the trends diverge
112 (Figure 1). In general, discharge is decreasing across most stations, while upstream water inputs tend to
113 be increasing. We do not see evidence for discharge intensification at snowmelt-dominated stations, as has
114 been reported in other parts of HMA²⁶. Spring discharge trends tend to be more negative than annual-scale
115 trends – despite increasing spring snowmelt in much of our study area – providing further evidence that

116 snowmelt changes are not inducing strong spring discharge intensification in the central Himalaya. Further,
117 if we look at trends in the timing of accumulated discharge (i.e., when 25% or 50% of annual discharge is
118 reached), we find that these thresholds are generally crossed later in the year for high-elevation and snow-
119 covered catchments (Supplemental Figure S5). We thus posit that spring snowmelt intensification is not a
120 major factor in our study area.

121 **Seasonal Correlation Structure**

122 The short-term (e.g., last 30, 60, 90 days) relationship between discharge and rainfall or snowmelt will vary
123 throughout the year (Figure 2). During most of the year, rainfall is positively correlated with discharge; the
124 correlation is weaker during the spring when soils absorb early rainfall and snowmelt contributes significantly
125 to discharge, and in the late monsoon period, when rainfall diminishes, but excess water is still being
126 released from groundwater and saturated soils. This aligns well with previous findings noting that there
127 is significant transient groundwater storage in the Himalaya that buffers stream discharge during the post-
128 monsoon period²⁷. The strongest relationship between rainfall and discharge is during the fall season,
129 when plant-water uptake decreases and smaller rainfall events can be converted directly into discharge over
130 saturated post-monsoon soils. During the spring, snowmelt is more strongly correlated with discharge than
131 rainfall up until the start of the monsoon, but otherwise it is generally less correlated with discharge. During
132 the monsoon season, snowmelt-discharge relationships are dominantly negative, indicating that the rainfall
133 signal strongly overprints the influence of snowmelt; that is, low snowmelt can lead to high discharge if there
134 is high rainfall at the same time, hence weakening correlations or even turning them negative.

135 While some changes in this seasonal relationship were expected, we did not find significant trends in short-
136 term discharge correlation to either rainfall or snowmelt (Figure 2b,c); we note, however, a slight tendency
137 towards lower rainfall-discharge seasonal correlation throughout the year (Figure 2b). This indicates that
138 the general shape of seasonal correlation of discharge to rainfall and snowmelt has not shifted substantially
139 during our study period.

140 **Inter-Annual Correlation**

141 At the inter-annual time scale, Kendall's τ statistics are less influenced by short-term (i.e., seasonal) fluc-
142 tuations. We find that Kendall's τ statistics for rainfall-discharge are all positive, whereas the relationship
143 between snowmelt and discharge can be both positive and negative (Figure 3). High-elevation catchments
144 tend to have stronger rainfall-discharge correlations; these catchments have relatively less vegetation and
145 shallower soils, which can smooth out the rapid discharge response to rainfall in lower-elevation catchments.

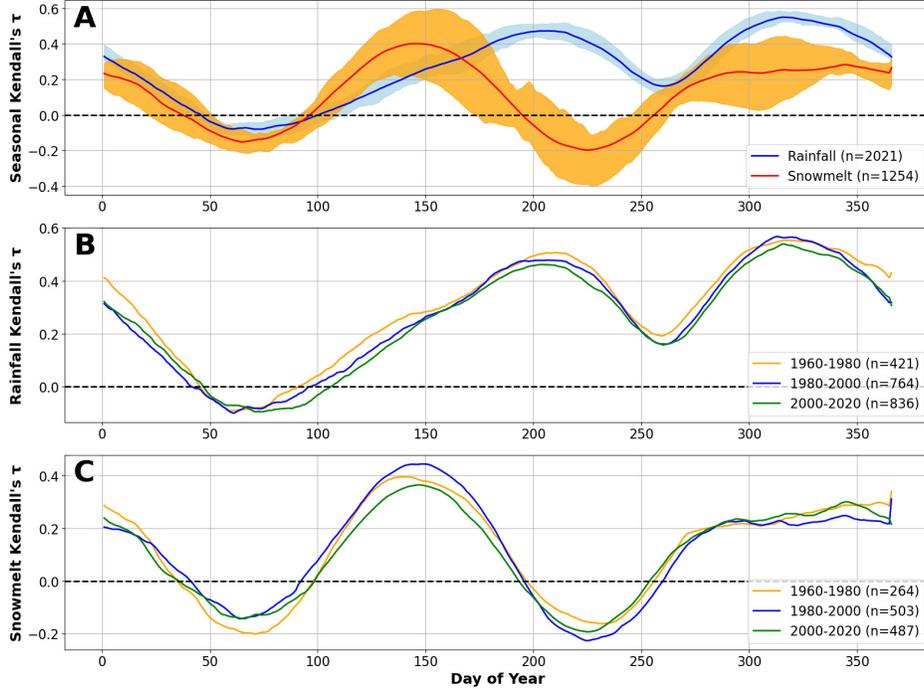


Figure 2: **Seasonal Correlation.** (A) Seasonal (90-day rolling) Kendall's τ statistics for rainfall (blue) and snowmelt (orange) correlated with discharge. Averaged by day-of-year and over all watersheds and all station-years; the number of station-years is summed in the legend. We generally note the most positive correlations during the monsoonal summer season. (B) Rainfall and (C) snowmelt Kendall's τ split by decade, showing generally similar seasonal correlation structures through time.

146 There is an east-west gradient in snowmelt-discharge correlation, with western Nepal being relatively less
 147 snowmelt driven. This is also reflected in average transit times, where western Nepal tends to have longer
 148 average snowmelt-discharge transit times (Figure 3D). Snowmelt transit times are almost all longer than
 149 rainfall transit times; this behavior is expected due to the longer flow paths from high-elevation snow-water
 150 storage to downstream discharge measurement stations.

151 Multi-Annual Changes in Correlation

152 Over longer (multi-annual) time periods, precipitation-discharge correlation averages over seasonal cycles;
 153 hence, changes in correlation structure are related to multi-year changes in the relationship between discharge
 154 and environmental factors. We can assess these changes station-wise, revealing a distinct spatial pattern in
 155 trends in both Kendall's τ statistics and transit times for both rainfall and snowmelt (Figure 4).

156 As all correlations are long-term mean positive between discharge and rainfall (Figure 3A), negative
 157 trends in Kendall's τ (Figure 4A) imply that the majority of discharge stations are becoming less strongly
 158 correlated with rainfall. Many stations have seen strong declines in discharge without commensurate negative
 159 changes in rainfall (Figure 1). Transit times for rainfall are generally increasing; this would be expected in

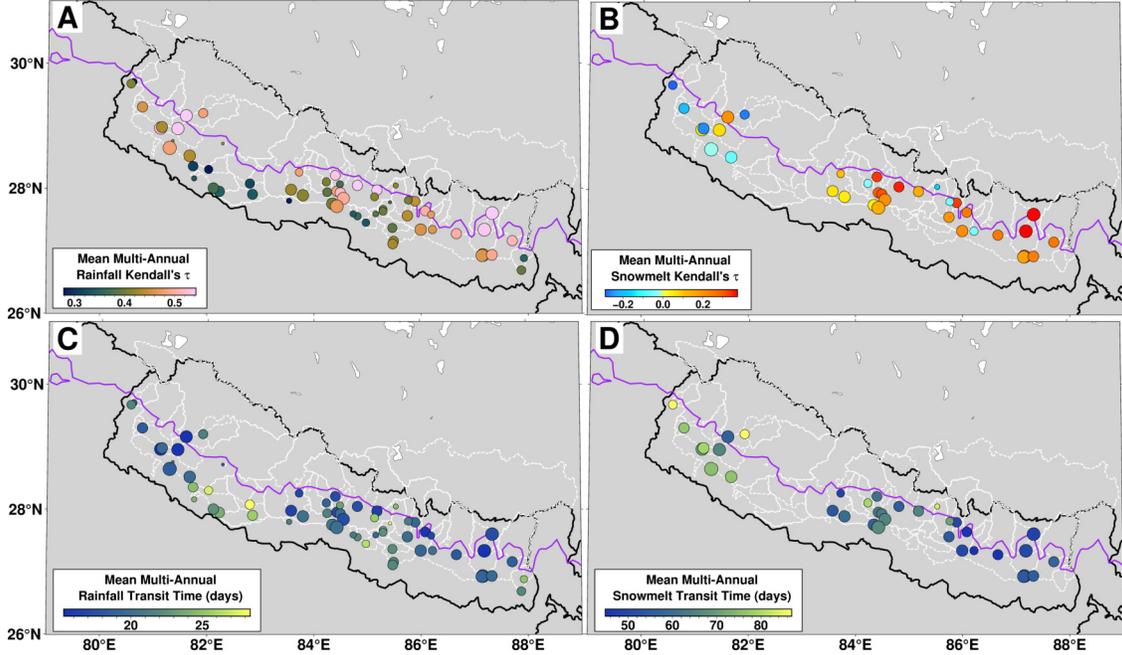


Figure 3: **Inter-Annual correlation.** Kendall's τ averages (three-year window) for (A) rainfall and (B) snowmelt. 2000 m elevation contour shown as purple line. Dots sized by catchment drainage area. Rainfall is positively correlated with discharge and we generally observe a higher correlation at higher elevations. Average transit times (three-year window) for (C) rainfall and (D) snowmelt. Rainfall transit times are comparable at medium and high elevations, but lower elevations tend to have longer transit times.

160 the case of increased transient rainfall storage or absorption by, e.g., vegetation.

161 Discharge-snowmelt correlations are dominantly decreasing, with stronger increases in transit time than
 162 those found between rainfall and discharge. However, there are also many catchments with decreasing transit
 163 times, indicating that in some cases, snowmelt is being more rapidly converted into downstream discharge.
 164 This could happen due to snowmelt intensification during the spring, or also due to shifts in the timing
 165 of snowmelt. Those same timing shifts could also increase transit times and decrease correlation, if, for
 166 example, snow is pushed to higher elevations, resulting in later melt (e.g., during the monsoon) and longer
 167 transit from high-elevation storage to low-elevation discharge measurement stations.

168 Discussion

169 Previous work has found both positive and negative discharge trends throughout Nepal, depending on the
 170 size and location of the catchment^{28;29;30;31;32}. We find a slight increase in annual catchment-aggregated
 171 total precipitation throughout Nepal using ERA5 data, alongside broadly decreasing annual average and
 172 spring discharge during the same time periods (Figure 1). We find statistically significant trends in rainfall-
 173 and snowmelt-discharge correlation, indicating multi-annual scale changes in the hydrological cycle of Nepal

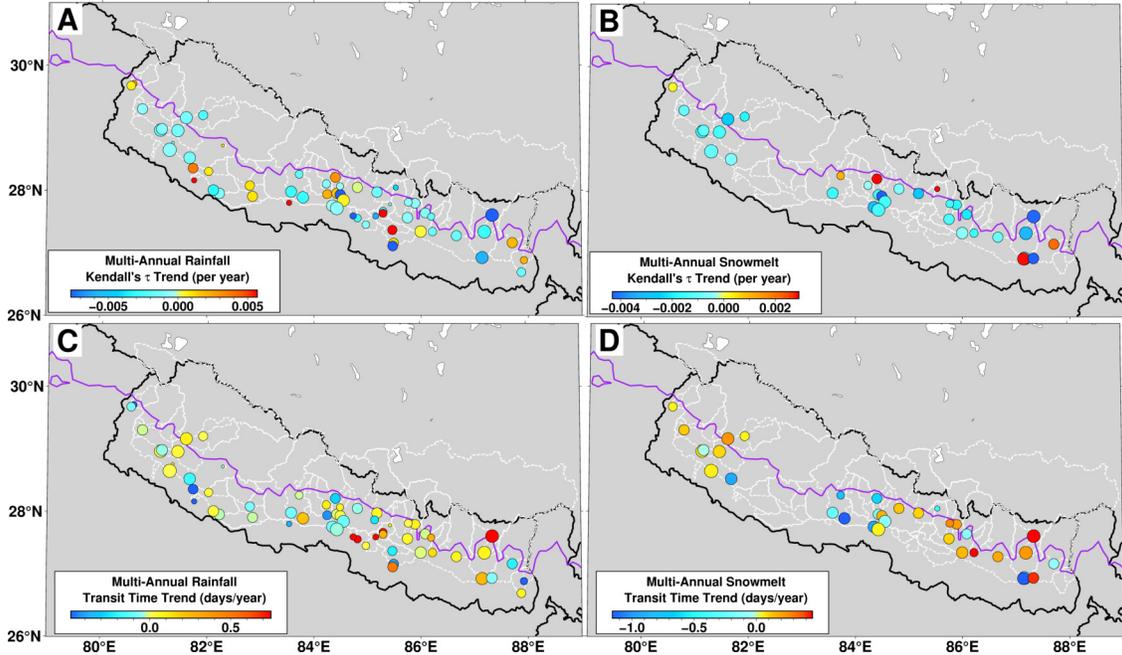


Figure 4: **Precipitation-Discharge Correlation Changes.** Kendall's τ trend between rainfall and discharge (A) and snowmelt and discharge (B). 2000 m elevation contour shown as purple line. Dots sized by catchment drainage area. Most trends are negative, suggesting a reduction of discharge correlation with both rainfall and snowmelt. Trend in transit time for (C) rainfall and (D) snowmelt. Trends in transit times for rainfall are generally positive, especially at higher elevations, suggesting that water storage in temporary reservoirs (e.g., soil moisture and groundwater) is increasingly important.

174 (Figure 4). There are many processes that can influence the rate at which upstream water inputs are
 175 converted into discharge, and hence the strength of the linear correlation and optimal lag time between
 176 watershed inputs and outputs.

177 Anthropogenic influences are one candidate driver; hydropower infrastructure and other dams have a
 178 particularly strong influence on how quickly water moves downstream. Changes in land use (e.g., replacing
 179 forests with agriculture) and other types of infrastructure – particularly roads – can also strongly impact
 180 watershed hydrology^{30;33;34}. If we consider both anthropogenic changes (roads, buildings, land cover) and
 181 natural structural changes (landslides) alongside trends in rainfall-discharge correlation, we find a negative
 182 correlation with Kendall's τ trends (Supplemental Figure S6): the more modified the watershed, the stronger
 183 the decrease in rainfall-discharge correlation. We hesitate, however, to present this as causal, as the environ-
 184 mental setting of highly-modified and less-modified watersheds can be strongly divergent (e.g., high-elevation
 185 and dry watersheds that are sparsely populated vs low-elevation and lush watersheds that are densely pop-
 186 ulated). Further, we lack information on the timing of landscape modifications, which limits our ability to
 187 directly link changing human land-use to rainfall-discharge correlation changes. It is likely, however, that
 188 human landscape modifications play a significant role in the strength of precipitation-discharge correlations

189 in our study area.

190 Ongoing environmental changes linked to precipitation shifts, temperature increases, and vegetation
191 changes are another potential driver (Figure 5). We find broadly increasing vegetation productivity through-
192 out the region, as well as an increased productive vegetation duration. These two factors together could lead
193 to more plant-water uptake, decreasing the availability of upstream water for groundwater and downstream
194 discharge. Warming has been well-documented in the region¹ (Figure 5C); increased temperatures have de-
195 creased snow persistence, decreased soil moisture, and encouraged the upwards migration of vegetation into
196 previously bare regions. Each of these factors could play a role in changing discharge characteristics, with
197 varied influence on rainfall-discharge and snowmelt-discharge correlations. At the broad scale, increased soil
198 moisture deficits due to rising temperatures are likely to reduce precipitation conversion into downstream
199 discharge, regardless of whether it is sourced as rainfall or snowmelt. The lack of increasing early-season
200 discharge (Figure 1) or shifts in the seasonal discharge cycle (Figure 2) imply that snowmelt changes are not
201 strongly propagating into discharge in our study area.

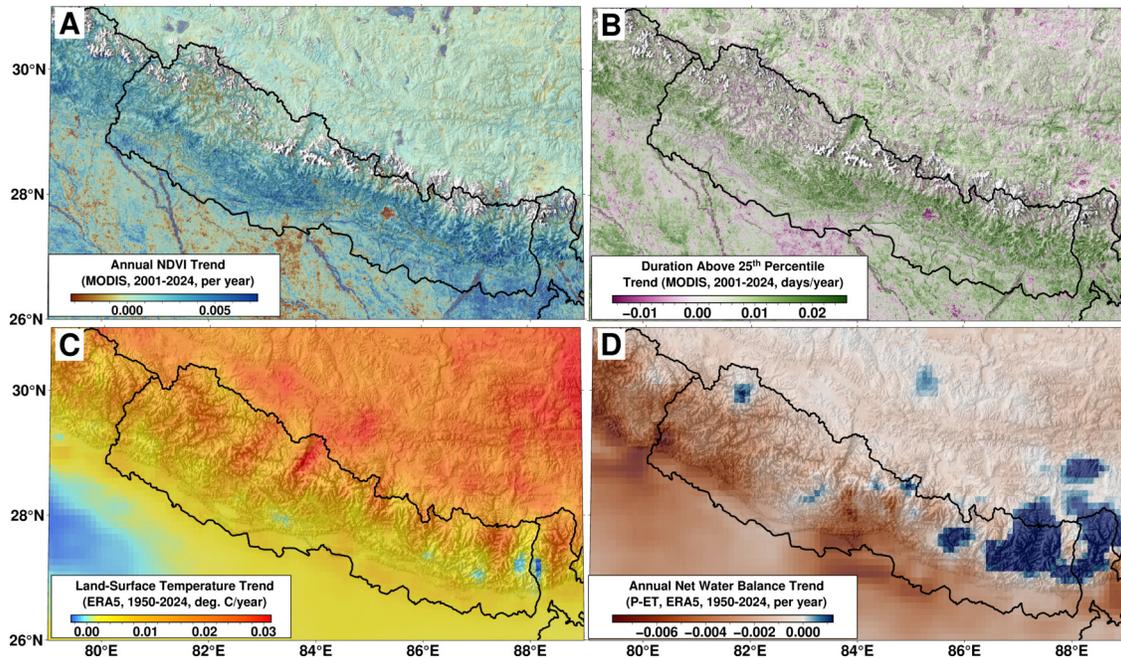


Figure 5: **Long-term Changes in Environmental Water Use.** (A) Long-term NDVI trend (MODIS, 2001-2024¹⁹). (B) Trend in duration above 25th percentile NDVI (MODIS, 2001-2024¹⁹). We observe positive trends in both parameters, suggesting an increase in chlorophyll content and productive season length. (C) Land-surface temperature trend (ERA5, 1950-2024¹⁸) is positive throughout with study area with higher trends at higher elevations³⁵ (Supplemental Figure S7). (D) Regional water balance trends (total precipitation - evaporation, ERA5, 1950-2024¹⁸) are negative with a few positive exceptions near glaciated areas.

202 Changes in NDVI and growing season length are positive across all elevation bins (Supplemental Figure

203 S7), though the strongest positive vegetation trends are at low elevations. We further find that temperature
204 trends are positive across all elevations, with the highest trends at high elevations. Finally, water deficits are
205 also increasing across all elevation bins, with the largest increases at low elevations (Supplemental Figure S7).
206 We thus conclude that changes in water use and stress are not confined to only some parts of each watershed,
207 but are rather a broad-based phenomenon that is impacting water usage throughout our study region. As
208 these environmental changes are present over entire watersheds, their expected impact is substantial; we
209 propose that these environmental changes are a primary driver of diminishing discharge throughout our
210 study area.

211 One additional factor that has been widely discussed in High Mountain Asia is changes in glacier con-
212 tribution to discharge^{36;37;15;3;38}, especially in the Indus basin. Previous investigations have suggested that
213 while discharge observations in large rivers may be biased – especially in the Indus River¹⁵ – there is a
214 general trend towards higher discharge in the northwestern Himalaya³⁶, alongside decreasing groundwa-
215 ter storage³⁹. Increasing discharge has been linked to increasing snow and glacier melt, especially in the
216 early summer season³⁶. We do not observe increased discharge in our study region (Figure 1), even in the
217 higher-elevation, sparsely vegetated, and glacier-covered catchments which are similar to those studied in
218 the northwestern Himalaya. Despite increased spring snowmelt in many catchments in our study area, we
219 further do not see increased spring discharge (Figure 1, Supplemental Figure S5). We thus posit that large-
220 scale environmental drivers (e.g., vegetation cover, soil-water deficits, increasing temperatures) are a more
221 important control on precipitation-discharge correlations than changes in glacier and snow-water resources
222 in the central Himalaya.

223 **Correlation and Transit Time Links**

224 If we consider both changes in precipitation-discharge correlation and transit time together, we can better
225 classify the changes in basin-scale water transport. For example, catchments that have decreased transit
226 times and increased correlation can be considered to be ‘flashier’ and more rapidly convert water into
227 discharge. Conversely, slower transit times and weaker correlation would indicate that water is taking longer
228 to move through the catchment. The majority of catchments fall into these two bins for rainfall-discharge
229 relationships (Figure 6).

230 While there remains noise in the data, there is a tendency for ‘flashier’ catchments to have positive
231 trends in available water and precipitation intensity. We hypothesize that these catchments are converting
232 any increased rainfall more rapidly into discharge. Conversely, slowing-transport catchments are acting more
233 like sinks, and correlate with higher water deficits and less intense precipitation (Figure 6).

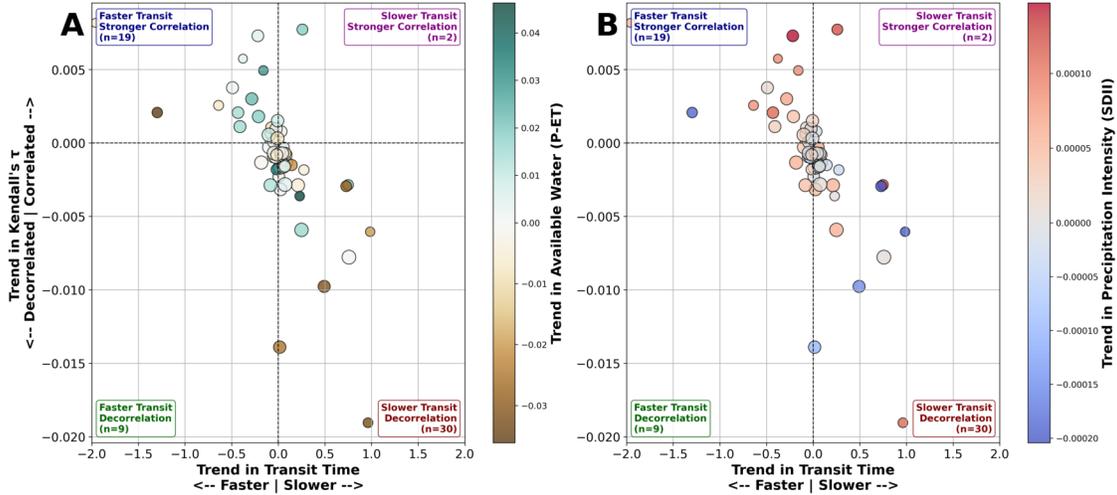


Figure 6: **Rainfall-Discharge Trend Classification.** Scatter plots of rainfall-discharge correlation trend direction compared to two potential drivers: (A) available water and (B) precipitation intensity. Only points with significant Kendall’s τ and transit time trends are shown. The number of points in each quadrant is shown in the corners of each plot. Dots sized by catchment drainage area.

234 The remaining two trend pairings (increased correlation and increased transit times, decreased corre-
 235 lation and decreased transit times) are less common. Only two catchments show an increased correlation
 236 and increased transit time; one potential mechanism would be longer flow paths (e.g., via hydropower reser-
 237 voirs) alongside a linear response to direct precipitation. Comparatively, more catchments show a signal of
 238 decreased correlation and decreased transit times, which could be a sign of more chaotic flow due to, e.g.,
 239 human landscape modifications. The majority of catchments in both of these less frequent bins, however,
 240 have very low trends, making their interpretation more difficult.

241 When we compare the correlation-transit time data to potential explanatory variables (Figure 6), we find
 242 that slowing and decorrelating catchments tend to have higher water deficits and decreasing precipitation
 243 intensities. Both factors have the potential to impact discharge – less intense but steady precipitation
 244 would likely take longer flow paths (e.g., through soil absorption and groundwater) and hence lead to longer
 245 transit times, especially if soil-moisture deficits are increasing due to plant-water uptake and increasing air
 246 temperatures (Figure 5). Conversely, if rainfall occurs as more intense and shorter storms, it is likely to lead
 247 to more overland flow and hence a more direct rainfall-discharge relationship. We lack, however, enough
 248 time-resolved data on changes in water budgets over the entire region to definitively link changes in coupled
 249 correlation-transit time to a set of mechanisms; further work would be needed to confirm the direct and
 250 coupled impacts of precipitation and water deficit changes on discharge throughout the region.

251 Changes in the precipitation-discharge relationship will likely be felt downstream, and these changes
 252 will not always have a negative impact. Increased transit times and a smoothing of the rainfall-discharge

253 relationship imply diminished peak flow intensities as more water is intercepted by vegetation and transiently
254 stored in soil and groundwater reservoirs. This increased buffering could help offset declines in snowmelt
255 as precipitation shifts towards rainfall in some catchments, as well as reduce the impact of intensifying
256 precipitation in the region⁴⁰. In already-dry catchments, however, increased evaporative water demand
257 and the general decrease in discharge (Figure 1) will influence ecosystems and communities that depend
258 on rivers. Further work is needed to better constrain how changing land cover will shape discharge in the
259 coming decades.

260 **Conclusions**

261 Understanding changes in the relationship between climate, precipitation, and discharge will be key to
262 regional water planning in the coming years. This is of particular importance given the growing role of
263 hydropower in national energy systems in the region. While the implied changes in watershed hydrology
264 found here are likely disruptive to natural ecosystems, in some cases, they may be rather beneficial to human
265 users. In particular, the weakening of the direct rainfall-discharge relationship, alongside only slight changes
266 in rainfall, implies a smoothing of the hydrograph, potentially minimizing the potential for flood events and
267 increasing the ability of local communities to draw on rivers, despite the decreases in average discharge.

268 **Acknowledgments**

269 T.S. acknowledges support from the DFG STRIVE project (SM 710/2-1) and the Universität Potsdam
270 Remote Sensing Computational Cluster.

271 **Data and Code Availability**

272 All model and remote sensing data sets used are publicly available. Python code used to pre-process and
273 export the data via Google Earth Engine is available on *Zenodo*. Discharge data was obtained from the
274 Nepali Department of Hydrology and Meteorology, and can be accessed from them directly.

275 **Author Contributions**

276 T.S. conceived and designed the study and interpreted the results with contributions from B.B. T.S. processed
277 all data and performed the numerical analysis. T.S. wrote the manuscript with contributions from B.B.

278 **Competing Interests**

279 The authors declare no competing interests.

280 **Additional Information**

281 Supplementary Information is available with this paper.

References

- [1] Masson-Delmotte, V. *et al.* Contribution of working group I to the sixth assessment report of the intergovernmental panel on climate change (Cambridge University Press Cambridge, UK, 2021).
- [2] Kang, S. *et al.* Review of climate and cryospheric change in the tibetan plateau. *Environmental Research Letters* **5**, 015101 (2010).
- [3] Immerzeel, W. W., Van Beek, L. P. & Bierkens, M. F. Climate change will affect the asian water towers. *Science* **328**, 1382–1385 (2010).
- [4] Rai, M. K. *et al.* Appraisal of empirical studies on land-use and land-cover changes and their impact on ecosystem services in nepal himalaya. *Sustainability* **15**, 7134 (2023).
- [5] Mukhtar, H. *et al.* Elevation-dependent vegetation greening and its responses to climate changes in the south slope of the himalayas. *Geophysical Research Letters* **52** (2025).
- [6] Maina, F. Z., Kumar, S. V., Albergel, C. & Mahanama, S. P. Warming, increase in precipitation, and irrigation enhance greening in high mountain asia. *Communications Earth amp; Environment* **3** (2022).
- [7] Hasson, S., Böhner, J. & Lucarini, V. Prevailing climatic trends and runoff response from hindukush–karakoram–himalaya, upper indus basin. *Earth System Dynamics* **8**, 337–355 (2017).
- [8] Bookhagen, B. & Burbank, D. W. Toward a complete himalayan hydrological budget: Spatiotemporal distribution of snowmelt and rainfall and their impact on river discharge. *Journal of Geophysical Research: Earth Surface (2003–2012)* **115** (2010).
- [9] Malik, N., Bookhagen, B. & Mucha, P. J. Spatiotemporal patterns and trends of indian monsoonal rainfall extremes. *Geophysical Research Letters* **43**, 1710–1717 (2016).
- [10] Han, J. *et al.* Streamflow seasonality in a snow-dwindling world. *Nature* **629**, 1075–1081 (2024).
- [11] Guo, Y. *et al.* Warming leads to both earlier and later snowmelt floods over the past 70 years. *Nature Communications* **16** (2025).
- [12] Musselman, K. N., Clark, M. P., Liu, C., Ikeda, K. & Rasmussen, R. Slower snowmelt in a warmer world. *Nature Climate Change* **7**, 214–219 (2017).
- [13] Smith, T. & Bookhagen, B. Changes in seasonal snow water equivalent distribution in high mountain asia (1987 to 2009). *Science Advances* **4**, e1701550 (2018). URL <https://www.science.org/doi/abs/10.1126/sciadv.1701550>. <https://www.science.org/doi/pdf/10.1126/sciadv.1701550>.
- [14] Smith, T., Bookhagen, B. & Rheinwalt, A. Spatiotemporal patterns of high mountain asia’s snowmelt season identified with an automated snowmelt detection algorithm, 1987–2016. *The Cryosphere* **11**, 2329–2343 (2017). URL <https://www.the-cryosphere.net/11/2329/2017/>.
- [15] Liu, J., Kang, S., Hewitt, K., Hu, L. & Xianyu, L. Large observational bias on discharge in the indus river since 1970s. *Scientific Reports* **8** (2018).
- [16] Zhu, Z. *et al.* Greening of the earth and its drivers. *Nature Climate Change* **6**, 791–795 (2016).
- [17] Chen, C., Riley, W. J., Prentice, I. C. & Keenan, T. F. Co₂ fertilization of terrestrial photosynthesis inferred from site to global scales. *Proceedings of the National Academy of Sciences* **119** (2022).
- [18] Hersbach, B. B. B. P. B. G. H. A. M. S. J. N. J. P. C. R. R. R. I. S. D. S. A. S. C. D. D. T. J.-N., H. Era5 monthly averaged data on single levels from 1940 to present (accessed on 08-2024). *Copernicus Climate Change Service (C3S) Climate Data Store (CDS)* (2023).
- [19] Didan, K. Modis/terra vegetation indices 16-day l3 global 250m sin grid v061 (2021).

- 323 [20] Schwanghart, W. & Scherler, D. Short communication: Topotoolbox 2 – matlab-based software for
324 topographic analysis and modeling in earth surface sciences. *Earth Surface Dynamics* **2**, 1–7 (2014).
325 URL <https://esurf.copernicus.org/articles/2/1/2014/>.
- 326 [21] Gorelick, N. *et al.* Google earth engine: Planetary-scale geospatial analy-
327 sis for everyone. *Remote Sensing of Environment* **202**, 18–27 (2017). URL
328 <https://www.sciencedirect.com/science/article/pii/S0034425717302900>. Big Remotely
329 Sensed Data: tools, applications and experiences.
- 330 [22] Mu, H. *et al.* A global record of annual terrestrial human footprint dataset from 2000 to 2018. *Scientific*
331 *Data* **9**, 176 (2022).
- 332 [23] Microsoft. Global ml building footprints (2022). URL <https://github.com/microsoft/GlobalMLBuildingFootprints>.
- 333 [24] OpenStreetMap contributors. Planet dump retrieved from <https://planet.osm.org> .
334 <https://www.openstreetmap.org> (2017).
- 335 [25] of Home Affairs, M. Nepal disaster report, 2024: focus on reconstruction and resilience (2024). URL
336 https://bipad.gov.np/uploads/publication_pdf/Nepal_Disaster_Report_Final_2024.pdf.
- 337 [26] Sharif, M., Archer, D. R., Fowler, H. J. & Forsythe, N. Trends in timing and magnitude of flow in the
338 upper indus basin. *Hydrology and Earth System Sciences* **17**, 1503–1516 (2013).
- 339 [27] Andermann, C. *et al.* Impact of transient groundwater storage on the discharge of himalayan rivers.
340 *Nature geoscience* **5**, 127–132 (2012). URL <https://doi.org/10.1038/ngeo1356>.
- 341 [28] Gautam, M. & Acharya, K. Streamflow trends in nepal. *Hydrological sciences journal* **57**, 344–357
342 (2012).
- 343 [29] Aryal, A., Shrestha, M., Aryal, S., Upadhyay, S. & Maharjan, M. Spatio-temporal variability of stream-
344 flow in major and medium rivers of nepal. *Journal of Hydrology: Regional Studies* **50**, 101590 (2023).
- 345 [30] Tuladhar, D., Dewan, A., Kuhn, M. & J. Corner, R. The influence of rainfall and land use/land cover
346 changes on river discharge variability in the mountainous catchment of the bagmati river. *Water* **11**,
347 2444 (2019).
- 348 [31] Khatiwada, K. R., Panthi, J., Shrestha, M. L. & Nepal, S. Hydro-climatic variability in the karnali
349 river basin of nepal himalaya. *Climate* **4**, 17 (2016).
- 350 [32] Sayedi, S. S., Singh, K. K., Fabrizio, M. C. & Nepal, S. Anthropogenic drivers and their impact on the
351 hydrological regime of nepal: a review. *Environmental Research Letters* **21**, 013003 (2026).
- 352 [33] Raiter, K. G., Prober, S. M., Possingham, H. P., Westcott, F. & Hobbs, R. J. Linear infrastructure
353 impacts on landscape hydrology. *Journal of Environmental Management* **206**, 446–457 (2018).
- 354 [34] Pennino, M. J., McDonald, R. I. & Jaffe, P. R. Watershed-scale impacts of stormwater green infrastruc-
355 ture on hydrology, nutrient fluxes, and combined sewer overflows in the mid-atlantic region. *Science of*
356 *the Total Environment* **565**, 1044–1053 (2016).
- 357 [35] You, Q. *et al.* Elevation dependent warming over the tibetan plateau: Patterns, mechanisms and
358 perspectives. *Earth-Science Reviews* **210**, 103349 (2020).
- 359 [36] Flores, J. A. *et al.* Accelerating river discharge in high mountain asia. *AGU Advances* **6** (2025).
- 360 [37] Bolch, T. *et al.* The state and fate of himalayan glaciers. *Science* **336**, 310–314 (2012).
- 361 [38] Lutz, A., Immerzeel, W., Shrestha, A. & Bierkens, M. Consistent increase in high asia’s runoff
362 due to increasing glacier melt and precipitation. *Nature Climate Change* **4**, 587–592 (2014). URL
363 <https://doi.org/10.1038/nclimate2237>.

- 364 [39] Dharpure, J. K., Howat, I. M. & Kaushik, S. Declining groundwater storage in the indus basin revealed
365 using grace and grace-fo data. *Water Resources Research* **61** (2025).
- 366 [40] Wulf, H., Bookhagen, B. & Scherler, D. Differentiating between rain, snow, and glacier contributions to
367 river discharge in the western himalaya using remote-sensing data and distributed hydrological modeling.
368 *Advances in Water Resources* **88**, 152–169 (2016).

Supplement to: Discharge Deficits in the Nepali Himalaya Linked to Greening and Warming

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List of Figures

S1	Data availability. Each available station is listed on the y-axis, with available data per day shown in black (long records) or gray (short records). Only stations with more than 10 years of data are used here.	2
S2	5th Percentile Discharge and Precipitation Trends. Changes in (A) Discharge, (B) Total Precipitation, (C) Spring Discharge, and (D) Spring Snowmelt. Annual aggregation to 5 th percentile before trend calculation.	3
S3	95th Percentile Discharge and Precipitation Trends. Changes in (A) Discharge, (B) Total Precipitation, (C) Spring Discharge, and (D) Spring Snowmelt. Annual aggregation to 95 th percentile before trend calculation.	3
S4	Example Discharge Distribution. Discharge z-scores over a short period, showing a subset of stations ranked from high to low elevation. Seasonal discharge distributions throughout the year follow a similar pattern across Nepal.	4
S5	Changes in Accumulated Discharge Timing. Day of year trends in the timing of discharge accumulation for the thresholds of (A) 25 th percentile and (B) 50 th percentile. Discharge tends to be accumulating later in the year across much of the study area.	4
S6	Impact of Human Infrastructure. Comparison of Rainfall-Discharge Kendall's τ trends to upstream infrastructure (A: roads, B: buildings, C: Human Footprint Index) and (D) landslide frequency. The relationships – while statistically significant – are generally weak.	5
S7	Role of Hypsometry in Environmental Trends. Comparison of (A) NDVI, (B) LST, and (C) Water Balance trends to hypsometry (250 m elevation bins). Each binned average line normalized to the maximum to show relative differences. Low elevations tend to have lower LST trends but stronger NDVI and water balance changes.	6

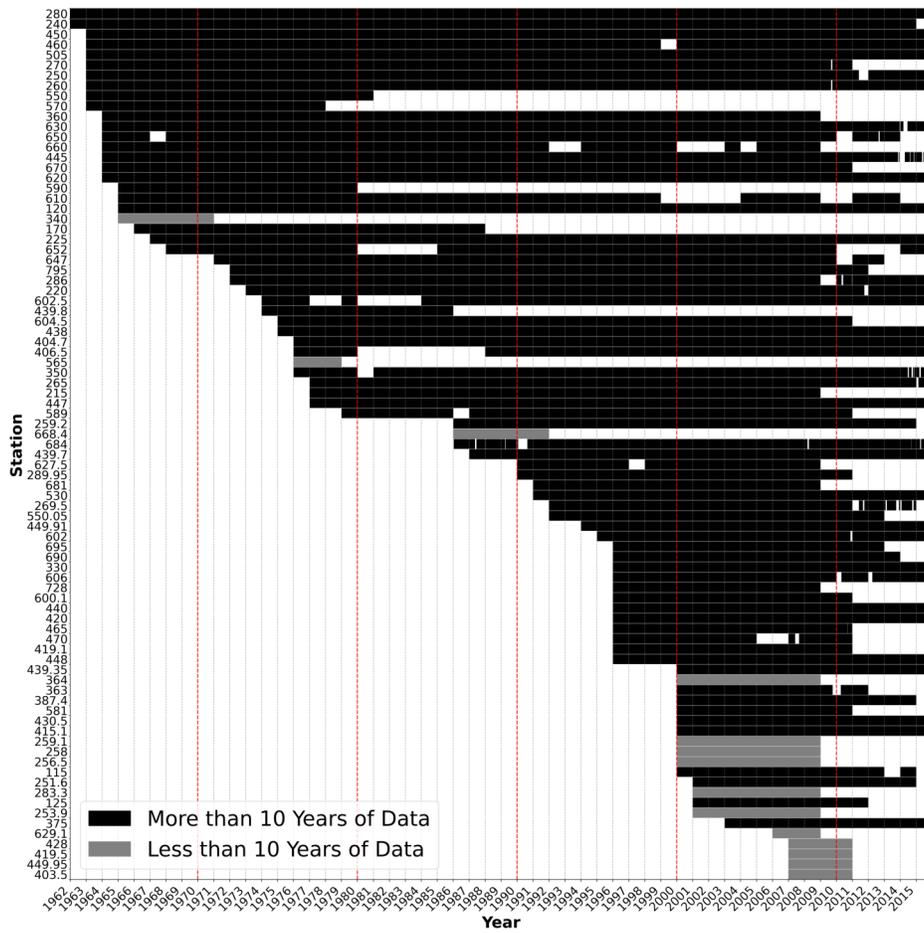


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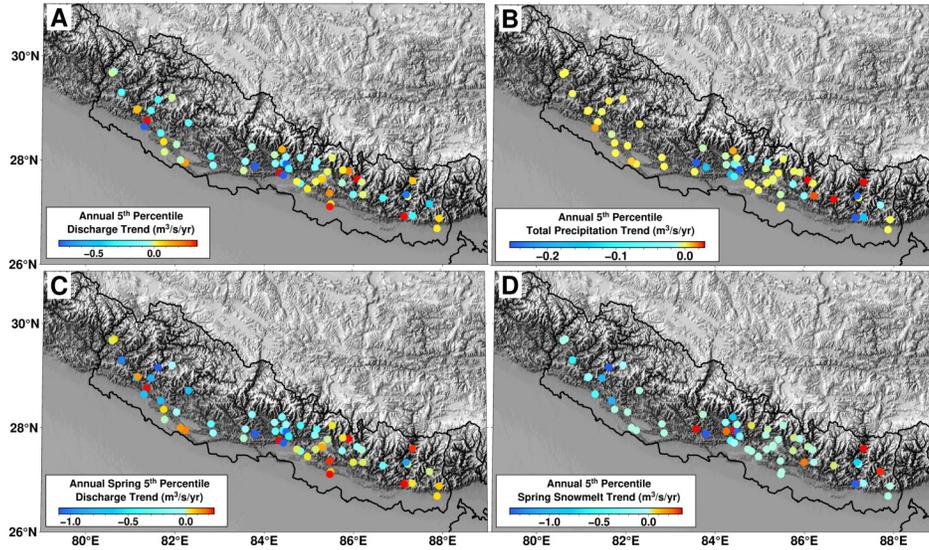


Figure S2: **5th Percentile Discharge and Precipitation Trends.** Changes in (A) Discharge, (B) Total Precipitation, (C) Spring Discharge, and (D) Spring Snowmelt. Annual aggregation to 5th percentile before trend calculation.

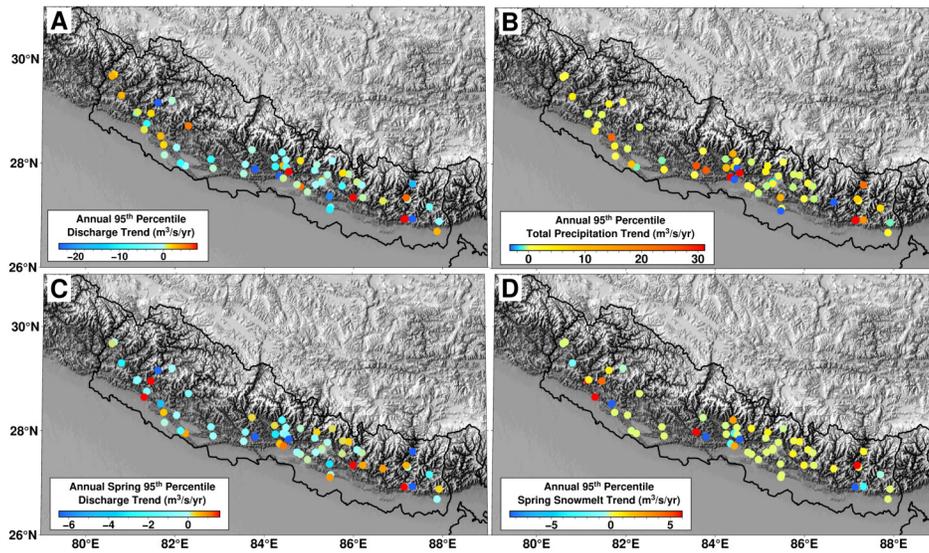


Figure S3: **95th Percentile Discharge and Precipitation Trends.** Changes in (A) Discharge, (B) Total Precipitation, (C) Spring Discharge, and (D) Spring Snowmelt. Annual aggregation to 95th percentile before trend calculation.

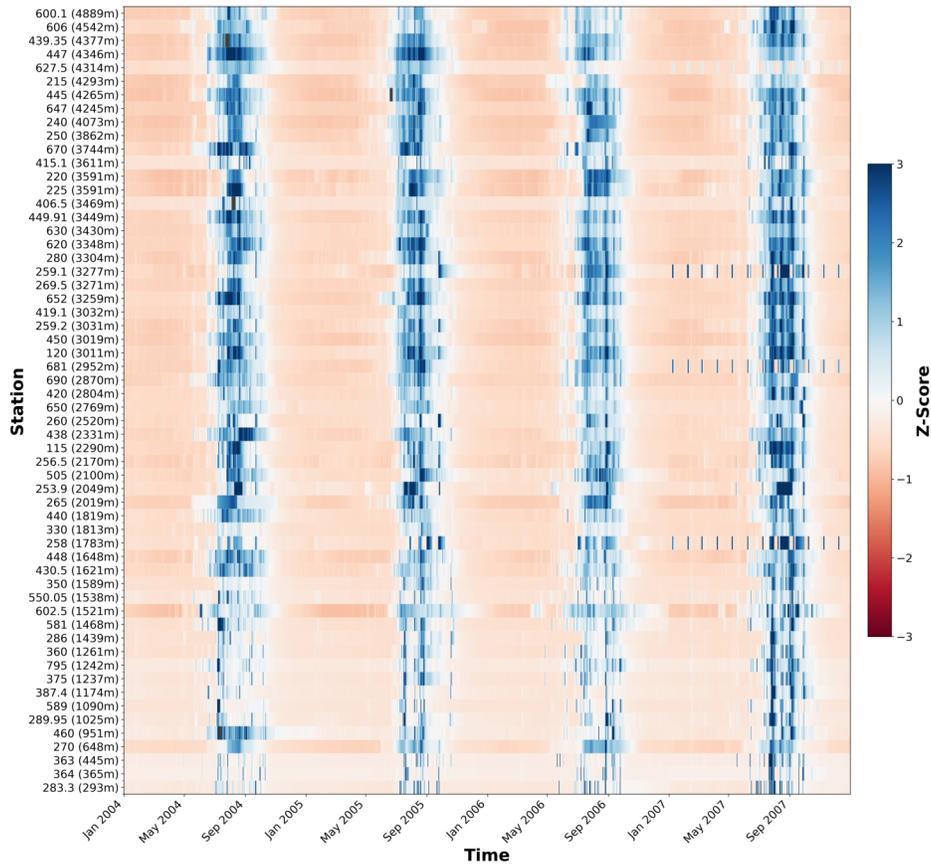


Figure S4: **Example Discharge Distribution.** Discharge z-scores over a short period, showing a subset of stations ranked from high to low elevation. Seasonal discharge distributions throughout the year follow a similar pattern across Nepal.

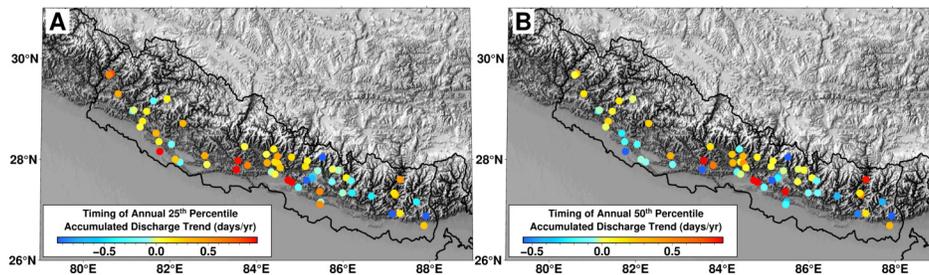


Figure S5: **Changes in Accumulated Discharge Timing.** Day of year trends in the timing of discharge accumulation for the thresholds of (A) 25th percentile and (B) 50th percentile. Discharge tends to be accumulating later in the year across much of the study area.

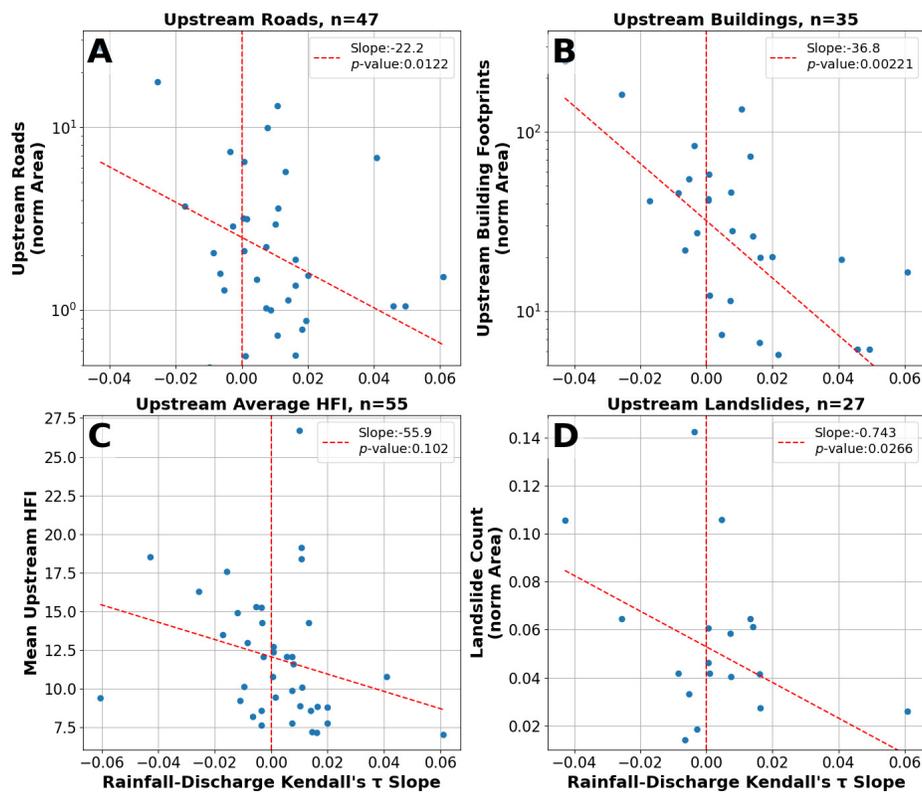


Figure S6: **Impact of Human Infrastructure.** Comparison of Rainfall-Discharge Kendall's τ trends to upstream infrastructure (A: roads, B: buildings, C: Human Footprint Index) and (D) landslide frequency. The relationships – while statistically significant – are generally weak.

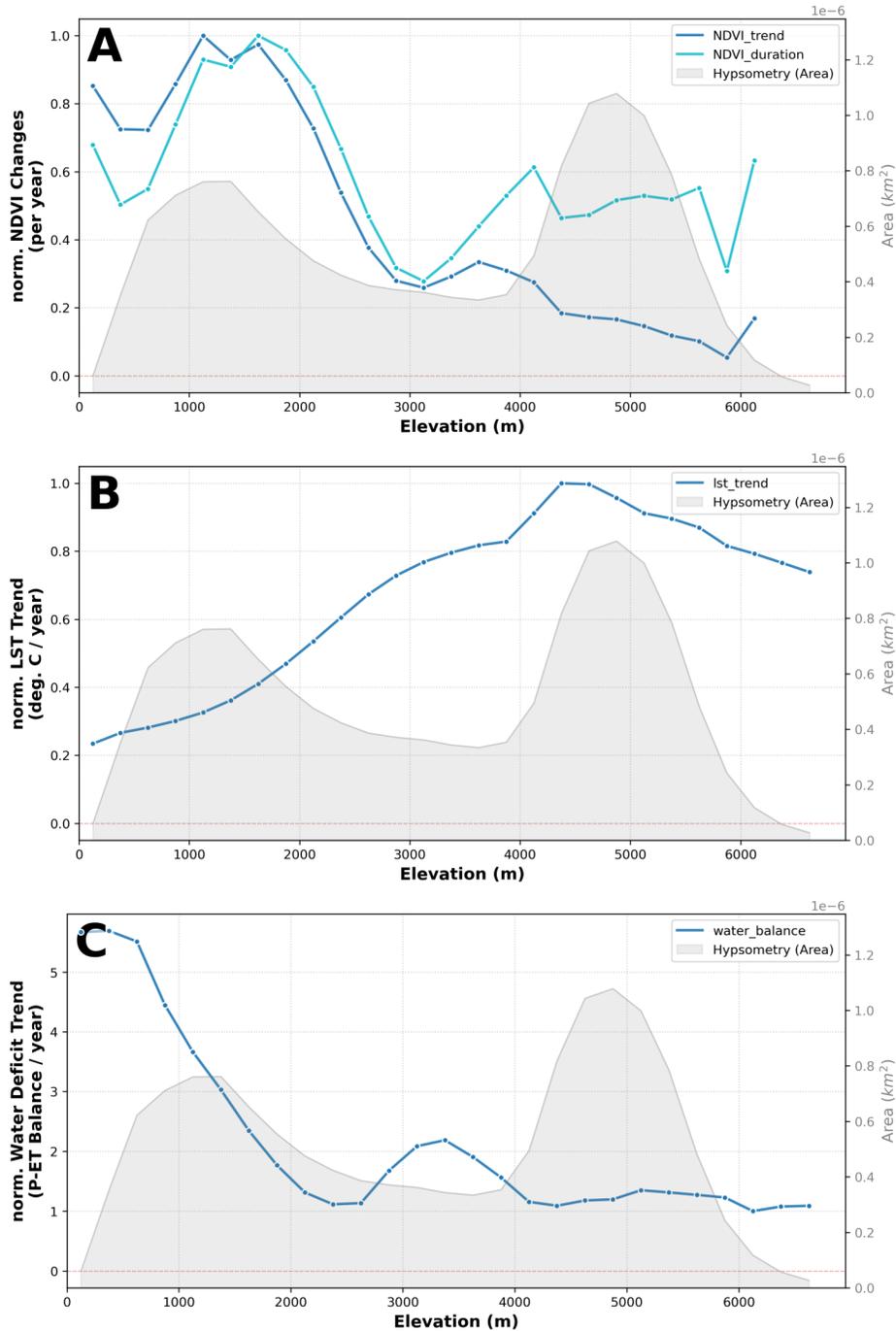


Figure S7: **Role of Hypsometry in Environmental Trends.** Comparison of (A) NDVI, (B) LST, and (C) Water Balance trends to hypsometry (250 m elevation bins). Each binned average line normalized to the maximum to show relative differences. Low elevations tend to have lower LST trends but stronger NDVI and water balance changes.