Geophysical Research Letters

RESEARCH LETTER
10.1029/2025GL121139

Forest Impacts on Peak Runoff Revealed by Accounting for the Effects of Climate

Shaozhen Liu[1,2,3], James W. Kirchner[2,4,5], Louise J. Slater[3], Marius G. Floriancic[2,6], Ilja van Meerveld[7], and Wouter R. Berghuijs[1]

[1]Department of Earth Sciences, Vrije Universiteit Amsterdam, Amsterdam, The Netherlands, [2]Department of Environmental Systems Science, ETH Zurich, Zurich, Switzerland, [3]School of Geography and the Environment, University of Oxford, Oxford, UK, [4]Swiss Federal Research Institute WSL, Birmensdorf, Switzerland, [5]Department of Forest Ecology and Management, Swedish University of Agricultural Sciences, Umeå, Sweden, [6]Department of Civil, Environmental and Geomatic Engineering, ETH Zurich, Zurich, Switzerland, [7]Department of Geography, University of Zurich, Zurich, Switzerland

Key Points:

- Forested catchments in the U.S. tend to have higher streamflow peaks because they are typically located in wetter climates
- After accounting for climate, however, peak runoff responses per unit rainfall decrease with increasing forest cover
- After accounting for climate, forested catchments have lower peak runoff responses per unit rainfall than cropland/grassland catchments

Supporting Information:

Supporting Information may be found in the online version of this article.

Correspondence to:

S. Liu,
shaozhen.liu@vu.nl

Citation:

Liu, S., Kirchner, J. W., Slater, L. J., Floriancic, M. G., van Meerveld, I., & Berghuijs, W. R. (2026). Forest impacts on peak runoff revealed by accounting for the effects of climate. *Geophysical Research Letters*, *53*, e2025GL121139. https://doi.org/10.1029/2025GL121139

Received 11 DEC 2025
Accepted 4 MAR 2026

Author Contributions:

Conceptualization: Shaozhen Liu, Wouter R. Berghuijs
Data curation: Shaozhen Liu, James W. Kirchner
Formal analysis: Shaozhen Liu
Funding acquisition: Shaozhen Liu, James W. Kirchner
Methodology: Shaozhen Liu, James W. Kirchner, Marius G. Floriancic
Project administration: Shaozhen Liu
Resources: Shaozhen Liu, James W. Kirchner
Software: Shaozhen Liu
Supervision: Shaozhen Liu, James W. Kirchner, Louise J. Slater, Wouter R. Berghuijs
Validation: Shaozhen Liu
Visualization: Shaozhen Liu

Abstract Land cover affects the runoff response of catchments. However, such land-cover effects remain difficult to decipher because experimental studies are site-specific, while large-sample analyses are often confounded by climate gradients that obscure the role of land cover. Site-to-site comparisons that ignore differences in antecedent wetness may overestimate runoff responses in forested catchments because they are typically found in humid climates. Here we quantify runoff responses to unit precipitation inputs and examine how they vary across 252 U.S. catchments with different land covers and forest fractions. For comparable antecedent wetness conditions (as quantified by antecedent streamflow), peak runoff responses decline as forest cover increases, with peak responses in forested catchments being 16%–63% lower than in catchments dominated by cropland or grassland. By accounting for climate-driven differences among catchments, our approach isolates the influences of land cover on reducing peak flows, which are often masked by climate in large-sample analyses.

Plain Language Summary It is often challenging to identify how land cover affects peak river flows across many catchments because climate differences among catchments often mask land-cover effects. Here we quantify the runoff response per unit of rainfall in 252 U.S. catchments and minimize climate-driven differences by grouping runoff responses according to antecedent wetness at the time of rainfall. For similar antecedent wetness conditions, peak runoff response decreases as forest cover increases. Peak runoff response is 16%–63% lower in forested catchments than in catchments dominated by cropland and grassland. This indicates that forest impacts on peak river flows emerge after accounting for the effects of climate.

1. Introduction

Over the past centuries, much of Earth's land cover has been altered by human activities and global warming (Song et al., 2018; Winkler et al., 2021), and such changes are projected to continue (Alexander et al., 2017). Land-cover change can affect hydrological behavior (Andréassian, 2004; Blöschl et al., 2007). While urbanization can have significant hydrological impacts (Anderson et al., 2022; Blum et al., 2020; Coxon et al., 2024; Han et al., 2022), the most widespread land-cover changes globally involve vegetated surfaces (Winkler et al., 2021). In this study, we focus on the role of forest cover. Studies of the hydrological influences of forest-cover change commonly focus on total water yield or annual average streamflow (e.g., Farley et al., 2005; Jackson et al., 2005; M. Zhang et al., 2017). Forest effects on peak flows can also be substantial but are generally more difficult to study and are often poorly constrained (Rogger et al., 2017).

Paired-catchment studies (e.g., Brown et al., 2013; Ogden et al., 2013) and modeling studies (e.g., Barnes et al., 2023; Buechel et al., 2022; Salazar et al., 2012) have explored how land-cover change may affect peak flows of headwater catchments. There remains ongoing debate over whether these effects occur for larger events and in larger catchments. Some studies have reported that forest cover reduces peak flows only during small to medium rainfall events (e.g., Bathurst et al., 2011; Brown et al., 2005; Salazar et al., 2012). By contrast, others have found that at previously degraded sites, where soil infiltration increased after afforestation, forest cover also reduces peak flows during large storms (e.g., Lana-Renault et al., 2014; S. Liu et al., 2025; van Meerveld et al., 2019). Land-cover effects on streamflow tend to be clearer for small catchments and tend to diminish with increasing

Writing – original draft: Shaozhen Liu
Writing – review & editing: Shaozhen Liu, James W. Kirchner, Louise J. Slater, Marius G. Floriancic, Ilja van Meerveld, Wouter R. Berghuijs

catchment size (Bathurst et al., 2022; Blöschl et al., 2007; Buechel et al., 2022), but significant effects can occur in large catchments as well (Salazar et al., 2012; Silveira & Alonso, 2009). The systematic review of Filoso et al. (2017) highlighted that forest-cover expansion decreased peak flows in over 80% of the 43 included studies (comprising both empirical and model studies). Stratford et al. (2017) synthesized 71 case studies from Europe and came to broadly similar conclusions, but emphasized that decreased peak flows are clearer for small events than larger ones.

Streamflow-based analyses across a range of catchments within a region can evaluate general relationships between forest-cover (change) and hydrological response. A conventional way is to examine spatial patterns of streamflow signatures (such as quantiles of the flow distribution) and relate these to climate and landscape properties (e.g., Hall et al., 2022; Krishnaswamy et al., 2012, 2013; L. Zhang et al., 2012). For example, Krishnaswamy et al. (2012, 2013) examined 11 catchments in the Western Ghats (India) and found that forested catchments generated less streamflow and that their responses were less flashy (i.e., with smaller fractions of quickflow) than for degraded forests and exotic Acacia plantations on formerly forested land. By contrast, Hall et al. (2022) showed for 20 catchments in Puerto Rico (U.S.) that forested catchments had higher peak flows than deforested ones under both wet and dry antecedent rainfall conditions, suggesting that increases in forest cover do not reduce peak flow extremes. McEachran et al. (2023) examined the streamflow responses for low-relief glaciated catchments in the U.S. and found that forest disturbance could increase or decrease peak flows, and that the effects of forest disturbance were smaller than the effects of climatic variability and catchment scale.

The rise of large-sample hydrologic data sets has made it possible to evaluate land-cover effects for even larger numbers of catchments over larger areas. However, such studies often face challenges in detecting clear land-cover effects (Anderson et al., 2022; Floriancic et al., 2022; Slater et al., 2024). Anderson et al. (2022) studied the relationship between peak flows and forest-cover change for 729 U.S. catchments and found a non-significant average effect of forest-cover changes on streamflow. Addor et al. (2018) and Stein et al. (2021) studied how landscape attributes influence spatial patterns of streamflow signatures for 671 U.S. catchments, and found that peak flow and flood events were only weakly influenced by land cover. One reason for the lack of a clear land-cover effect in these studies may be that as the number of study sites and the spatial domain increase, the inferred effects of land cover become increasingly confounded by climate gradients, which exert a dominant control on peak flows (Addor et al., 2018; Berghuijs et al., 2019; Slater et al., 2024; Stein et al., 2021; Y. Zheng et al., 2023). It is challenging to disentangle the influence of land cover from climate by simply stratifying study catchments by climate gradients (e.g., differences in precipitation or aridity) because land cover is strongly confounded with climate (i.e., forests are more common in wetter catchments), meaning that stratifying by climate gradients also implicitly stratifies by land cover. Therefore, in large-sample studies, particularly those spanning regions with large gradients of climatic aridity, stratifying by climate gradients may not be an effective way to explore the influence of land-cover on the runoff response. Instead, because climate influences peak runoff response by controlling antecedent catchment wetness, stratifying runoff responses by antecedent streamflow (Q_{ant}) targets the hydrologic state governing runoff generation and thereby reduces the confounding effect of climate.

Here, we use a novel approach to infer the effects of forest cover on peak flows, by combining a recently developed method that quantifies rainfall-runoff responses (Ensemble Rainfall-Runoff Analysis (ERRA), Kirchner, 2024a) with data from 252 U.S. catchments dominated by different land covers (Addor et al., 2017; Gauch et al., 2020). We address the confounding effect of climate by stratifying the runoff responses by antecedent wetness conditions (quantified by antecedent streamflow). We then examine the spatial pattern of peak runoff responses per unit rainfall and reveal systematic gradients in peak runoff responses with forest cover. We use this approach to examine the effects of land cover (and forest fraction) on the runoff response because these spatial differences in runoff response reflect the net (long-term) effects of land cover on hydrological processes and can help to understand the effects of forest cover change on peak flows.

2. Methods

2.1. Ensemble Rainfall-Runoff Analysis and Runoff Response Distributions

Many conventional methods for quantifying runoff response behavior, such as unit hydrographs, assume that runoff is proportional to precipitation. However, real-world hydrological systems can be highly nonlinear and nonstationary (Kirchner, 2009). Ensemble Rainfall-Runoff Analysis (ERRA) quantifies a catchment's nonlinear, nonstationary response to precipitation directly from observational data using nonlinear deconvolution and de-

10.1029/2025GL121139

mixing (Kirchner, 2022, 2024a), thereby providing a nonlinear and nonstationary extension of unit hydrograph approaches. ERRA is a data-driven and model-independent method; as such, it characterizes and quantifies how catchments behave without making any assumptions about the mechanisms underlying that behavior. The mathematical foundations of ERRA are documented and benchmarked by Kirchner (2022), and illustrative applications to hydrological systems are presented by Kirchner (2024a).

The weighted average runoff response distribution (RRD) obtained from ERRA quantifies the incremental runoff response per millimeter of hourly precipitation as a function of lag time (Kirchner, 2024a, Figure S1b in Supporting Information S1). While conceptually similar to a unit hydrograph, it accounts for the underlying nonlinearity and non-stationarity. The weighted average RRD represents the average or typical runoff response behavior of a catchment, while RRDs stratified by antecedent wetness conditions represent the runoff response behavior for specific wetness conditions before the rain falls (Figure S1c in Supporting Information S1). See Figure S1 in Supporting Information S1 for an illustration of how to interpret average RRDs and stratified RRDs for an example catchment.

Due to the lack of hourly soil-moisture observations, we use streamflow 6 hr before rain falls to represent the antecedent wetness conditions. Antecedent streamflow is a widely used index for characterizing catchment antecedent wetness conditions (James & Roulet, 2009; Kirchner, 2009; Tarasova et al., 2018). The three antecedent streamflow intervals we use are <0.05, 0.05–0.15, and >0.15 mm hr^{-1}. The RRD peak height reflects the peak runoff response to an additional mm of hourly rainfall, above any antecedent streamflows. Therefore, we use the peak heights of RRDs to measure the effects of rainfall on subsequent peak flow conditions for each of the three antecedent streamflow ranges.

2.2. Data

We derived RRDs for catchments throughout the United States using hourly precipitation and streamflow time series from Gauch et al. (2020), who provide records for 516 CAMELS catchments (Addor et al., 2017; Newman et al., 2015) from 1980 to 2020. In this data set, streamflow is obtained from the USGS Water Information System through the Instantaneous Values REST API (United States Geological Survey, 2021) and aggregated to hourly resolution for each catchment. Precipitation is taken from the hourly NLDAS-2 product, which contains hourly meteorological data since 1979 (Xia et al., 2012).

We estimated the RRD for the snow-free season to avoid snowmelt influences on the rainfall runoff-response. The presence of snow was inferred using daily Normalized Difference Snow Index (NDSI) values extracted from 2001 to 2020 MODIS satellite data using Kirchner et al. (2020b)'s robust estimation approach, which minimizes artifacts due to clouds. For each catchment, we computed the 90th percentile of the NDSI for each month of each year and considered the months in which the 90th percentile of the NDSI value was <-0.2 as snow-free. Because the NDSI data span 2001–2020 (20 years), while the hourly hydrologic data used to derive RRDs extends back to 1980, we classified a month as snow-free in a given catchment if it was snow-free in 16 or more of the 20 years (≥80%).

We compared peak heights of both average RRDs and stratified RRDs in catchments with different forest fractions and land covers to reveal land-cover effects on the runoff response. The forest fraction and dominant land cover were derived from the CAMELS catchment attributes data set (Addor et al., 2017). We focus on catchments with four dominant landcover types, including three types of forests (i.e., evergreen needleleaf, mixed, and deciduous broadleaf) and one non-forested catchment type (combining cropland, grassland, and cropland or natural vegetation mosaics). We limited our selection to catchments for which the dominant landcover occupies at least 70% of the catchment's total area, resulting in a set of 458 catchments.

From the 458 catchments with one of the four dominant landcovers, we had to eliminate 206 catchments that had insufficient usable data to complete the calculations, or to quantify the RRDs reliably (thus yielding RRDs with unrealistic shapes or very large standard errors, for example, Figure S2 in Supporting Information S1). In these cases, there is insufficient information in the data to statistically derive a catchment's nonlinear and nonstationary response to precipitation (e.g., because the timeseries are too short, the data is of too low quality, or the catchment response is too decoupled from precipitation). These catchments were primarily located in the western mountainous regions, with too few rain events occurring during the snow-free season, and the Great Plains, with too few rainfall events occurring during high antecedent wetness conditions ($Q_{ant} > 0.15$ mm hr^{-1}). Of the remaining 252

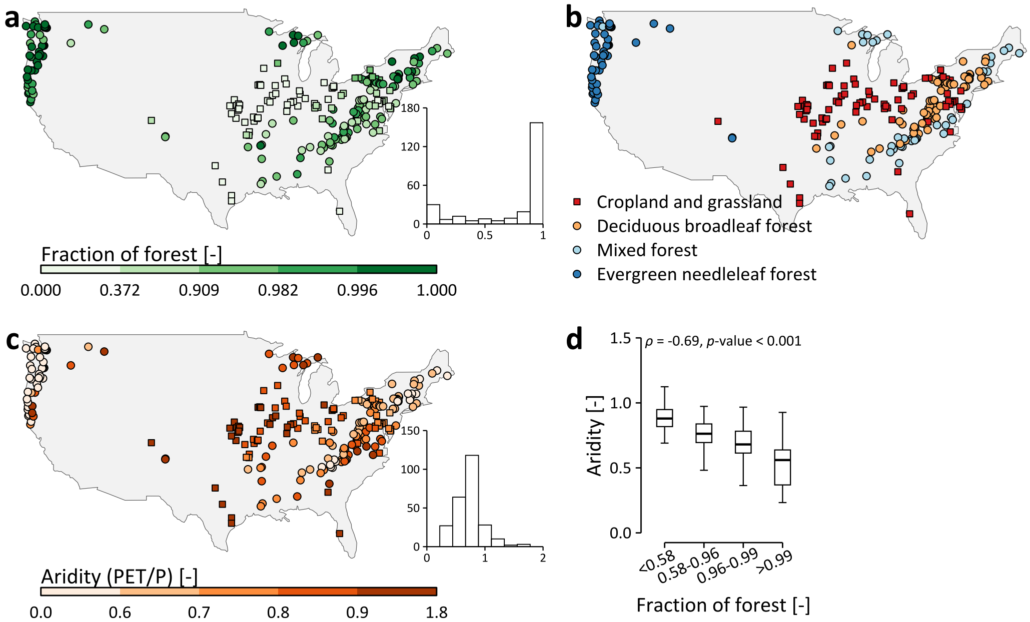

Figure 1. Geographic distributions of the 252 catchments and their vegetation and climate characteristics. (a–c) Geographic distributions of forest fraction, dominant land cover, and climate aridity (PET/P). Forested catchments are shown as circles, and non-forested catchments as squares. (d) Variation in aridity for catchments with different forest fractions; catchments with higher forest cover tend to be located in more humid regions. The box represents the interquartile range, the horizontal line through the box represents the median, and the whiskers extend to 1.5 times the interquartile range (outliers not shown). The bins of forest cover for the boxplots contain equal numbers of catchments ($n = 63$).

catchments, 49 are classified as evergreen needleleaf forest catchments (data coverage 22–34 years), 44 as mixed forest catchments (data coverage 23–39 years), 81 as deciduous broadleaf forest catchments (data coverage 13–39 years), and 78 as cropland and grassland catchments (data coverage 13–38 years; including 25 cropland, 11 grassland, and 42 cropland or natural vegetation mosaic catchments).

We also extracted additional catchment properties from CAMELS (Addor et al., 2017) to assess factors beyond land cover that may influence the runoff response, including: catchment area (km^2), climate aridity (PET/P), mean slope ($m\ km^{-1}$), soil conductivity ($cm\ hr^{-1}$), and geological permeability (m^2). The median and range of data coverage and catchment properties for each dominant land cover are listed in Table S1 in Supporting Information S1. The geographic distribution of the 252 study catchments is shown in Figure 1, with their forest fraction (Figure 1a), dominant land cover (Figure 1b), and climate aridity (Figure 1c). For the 252 study catchments, catchment areas range from 6 to 1,980 km^2, with an average of 430 km^2 and a median of 256 km^2. Catchments with higher forest cover are generally located in the more humid regions (Figure 1d). The Spearman rank correlation between forest fraction and aridity is −0.69 (p-value < 0.001). Catchments with higher forest cover fractions also tend to be smaller (Figure S3 in Supporting Information S1; Spearman's $\rho = -0.22$, p-value = 0.001), have larger mean slopes (Figure S3 in Supporting Information S1; $\rho = 0.68$, p-value < 0.001), and have higher soil conductivities (Figure S3 in Supporting Information S1; $\rho = 0.52$, p-value < 0.001).

2.3. Isolating Forest Cover Effects From Climate

We first quantify the univariate (Spearman rank correlation) and multivariate (multiple linear regression) relationships between the conventional peak flow signature (Q_1, the flow exceeded 1% of the time) and land cover and climate aridity. Second, we examine the same relationships for peak heights of average RRDs. Finally, we assess these relationships for peak heights of stratified RRDs. In the first approach, relationships between Q_1 and land cover can be confounded by climate, since Q_1 depends on both precipitation and its conversion to runoff. Forest cover is typically higher in humid catchments (Figure 1d), and thus Q_1 tends to be higher in such areas for two reasons: (a) precipitation rates are greater and (b) the conversion of precipitation to runoff is influenced by climate, as aridity strongly controls how much precipitation becomes streamflow (Arora, 2002; Berghuijs et al., 2014; Padrón et al., 2017). Thus, higher Q_1 in forested catchments can partly reflect climate rather than the influence of land cover on runoff generation. In the second approach, relationships between peak heights of average RRDs and land cover remain partly confounded by climate. Although average RRDs represent the runoff response per unit rainfall, the conversion of rainfall to runoff still depends on aridity, so peak heights across land covers still reflect some climatic influence (albeit to a lesser extent compared to the relationship between Q_1 and land cover). In the third approach, relationships between peak heights of RRDs for similar antecedent wetness conditions (quantified by antecedent streamflow) and land cover are largely unconfounded by climate. Because aridity affects the runoff response mainly through antecedent wetness, stratifying RRDs by three antecedent streamflow intervals (<0.05, 0.05–0.15, and >0.15 mm hr^{-1}) allows comparisons across climate zones for similar antecedent wetness conditions, thereby minimizing the confounding effects of climate (see the lower three rows of Figure 2).

3. Results and Discussion

3.1. Relationships Between Q_1 and Land Cover and Aridity

Raw correlations suggest that Q_1 is higher in more forested catchments, but this difference may reflect climate effects rather than land-cover differences (Figures 2a–2d, Figures S4a and S4b in Supporting Information S1). The univariate Spearman rank correlations show that Q_1 is significantly higher in more humid regions (Figure 2b; Spearman's $\rho = -0.67$, p-value < 0.001) and also higher in catchments with greater forest cover (Figure 2c; $\rho = 0.43$, p-value < 0.001). Catchments with the highest (>0.99) forest cover fractions have a median Q_1 (0.85 mm hr^{-1}) that is 80% higher than in the lowest (<0.58) forest cover group (0.47 mm hr^{-1}, Figure 2c). The median Q_1 is highest in evergreen needleleaf forest catchments (1.30 mm hr^{-1}) and is 169% higher than in cropland and grassland catchments (0.48 mm hr^{-1}, Figure 2d). By contrast, multiple linear regression analyses of Q_1 with aridity and forest fraction indicate that a higher forest cover reduces Q_1, but the standardized effect on Q_1 (regression slope multiplied by the driver's standard deviation) of forest fraction is ∼6 times smaller than that of aridity (Table S2 in Supporting Information S1). Thus, the study catchments show a likely spurious positive univariate relationship between forest cover, and after accounting for climate using the multiple linear regression, forest cover effects on Q_1 appear uncertain because aridity effects dominate (Figures 2a–2d and Table S2 in Supporting Information S1).

3.2. Peak Heights of Average RRDs Versus Land Cover and Aridity

Peak heights of average RRDs do not covary significantly with forest cover, but this may still reflect some residual climate effects rather than an absence of land cover effects on runoff response (Figures 2e–2h, Figure S4c and S4d in Supporting Information S1). Univariate Spearman rank correlations show that the relationship between peak height of the average RRD and forest fraction is weak and insignificant (Figure 2g; $\rho = -0.02$, p-value $= 0.81$) and is thus much weaker than the relationship between Q_1 and forest fraction (Figure 2c; $\rho = 0.43$, p-value < 0.001). The correlation between average RRD peak height and climate aridity (Figure 2f; $\rho = -0.25$, p-value < 0.001) is also notably weaker than the relationship between Q_1 and climate aridity (Figure 2b; $\rho = -0.67$, p-value < 0.001). This is logical because the average RRDs represent the runoff response per unit rainfall, whereas Q_1 can be expected to increase with increasing rainfall. Multiple linear regression analysis of RRD peak heights indicates that the standardized effect of aridity is of a similar magnitude as that of forest fraction (Table S2 in Supporting Information S1). Furthermore, there are no clear systematic differences in the peak heights of average RRDs among land cover classes, with substantial overlap in the interquartile ranges across different classes (Figure 2h). Thus, is the catchments show no clear relationship between forest cover and peak heights of average RRDs, but this may reflect some residual confounding climate effects rather than an absence of effects of land cover on runoff response (Figures 2e–2h and Table S2 in Supporting Information S1).

3.3. Peak Heights of Stratified RRDs Versus Land Cover and Aridity

In contrast to the peak heights of the average RRDs, peak heights of the RRDs stratified by antecedent wetness (as quantified by antecedent streamflow Q_{ant}) decrease significantly as forest cover increases, while relationships between peak height and climate aridity are generally weak and not consistently significant (Figures 2i–2t, Figures S4e–S4j in Supporting Information S1). Stratified RRD peak heights exhibit weak and insignificant correlations with aridity for antecedent wetness Q_{ant} in the ranges of 0–0.05 mm hr^{-1} (Spearman $\rho = 0.03$, p-value $= 0.63$)

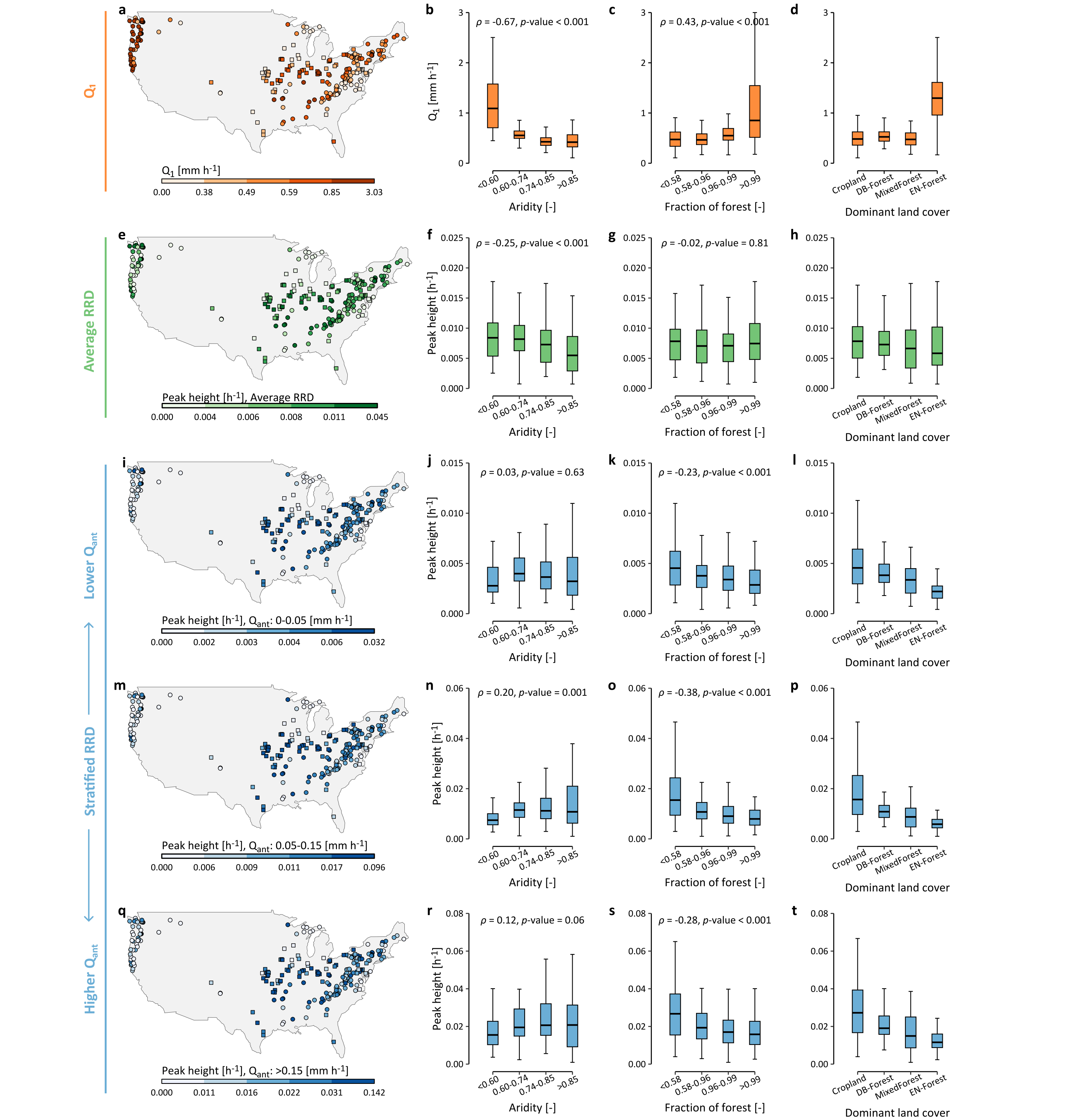

Figure 2. Disentangling forest-cover effects on runoff response from climate effects. (a–d) Spatial patterns of Q_1 (the flow exceeded 1% of the time) and how it varies with climate aridity and land cover. (e–h) Spatial patterns of peak height of average runoff response distributions (average RRD) and how it varies with climate aridity and land cover. (i–t) Spatial patterns of the peak height of RRDs stratified by antecedent wetness conditions (stratified RRDs) and how they vary with climate aridity and land cover. The three antecedent wetness conditions are based on antecedent streamflow intervals Q_{ant}: <0.05, 0.05–0.15, and >0.15 mm hr^{-1}. The Spearman rank correlation coefficient and corresponding p-value are printed in the upper corner of the box plots with aridity and forest cover. In the rightmost column, DB-Forest indicates deciduous broadleaf forest, EN-Forest indicates evergreen needleleaf forest, and Cropland indicates cropland and grassland catchments. The bins for the boxplots of aridity and forest fraction contain equal numbers of catchments (n = 63). The numbers for catchments dominated by cropland and grassland, deciduous broadleaf forest, mixed forest, and evergreen needleleaf forest are 78, 81, 44, and 49, respectively.

10.1029/2025GL121139

and >0.15 mm hr^{-1} (ρ = 0.12, p-value = 0.06), and weak correlations with aridity for antecedent streamflow values in the range of 0.05–0.15 mm hr^{-1} (ρ = 0.20, p-value = 0.001) (Figures 2j, 2n, and 2r). By contrast, stratified RRD peak heights exhibit statistically significant decreases with forest fraction for all antecedent wetness ranges: 0–0.05 mm hr^{-1} ($\rho = -0.23$), 0.05–0.15 mm hr^{-1} ($\rho = -0.38$), and >0.15 mm hr^{-1} ($\rho = -0.28$) (Figures 2k, 2o, and 2s; p-values all <0.001). Across all the antecedent wetness classes, the median peak height of RRDs in catchments in the highest (>0.99) forest fraction group is typically 37%–49% lower than in the lowest (<0.58) forest cover fraction group.

Catchments dominated by forest cover have lower peak runoff responses than those dominated by croplands or grasslands (Figures 2l, 2p, and 2t). Evergreen needleleaf forest catchments have the lowest peak response, followed by mixed and deciduous forests, with cropland and grassland catchments having the highest peak response. Across the antecedent wetness classes, peak heights of stratified RRDs in forested (deciduous broadleaf forest, mixed forest, and evergreen needleleaf forest) catchments are typically 16%–63% lower than those in croplands and grasslands. The relationships between peak height of stratified RRDs and dominant land cover or forest fraction are rather insensitive to forest cover class boundaries, the binning strategy used to group catchments, antecedent streamflow classes, and the temporal resolution of data (Figures S5–S7 in Supporting Information S1).

Multiple linear regression of peak height of stratified RRDs shows that a 1-standard-deviation change in forest fraction has an effect on peak runoff response that is ∼5–15 times larger than the effect of a 1-standard-deviation change in aridity (Table S2 in Supporting Information S1). In other words, after stratifying RRDs by antecedent streamflow, the influence of climate becomes weak and the influence of forest cover becomes dominant (Figures 2i–2t and Table S2 in Supporting Information S1).

The effects of land cover on runoff response become even clearer in the stratified RRDs averaged across all catchments in each dominant land cover group (Figure 3). For the same antecedent wetness condition, forested catchments have lower response peak heights than cropland and grassland catchments do. The evergreen needleleaf forest catchments have the lowest peak heights, followed by the mixed forest and deciduous broadleaf forest, while the cropland and grassland catchments have the highest peak heights. Time to peak shows no systematic differences between the forested and non-forested catchments but the recession tends to be less steep in forested catchments, reflecting their frequently higher baseflows (e.g., Hall et al., 2022; Krishnaswamy et al., 2013; Price et al., 2010). The time to peak of stratified RRDs also shows little variation with forest cover fraction or land cover classes (Figure S8 in Supporting Information S1). This suggests that even under similar climatic conditions (i.e., when the confounding effects of climate are minimized), variations in time to peak are primarily driven by factors other than land cover.

The volume of runoff generated per unit of rainfall often increases more than proportionally with precipitation intensity (Kirchner, 2024a). Precipitation frequency curves for the four dominant land covers show that, for recurrence intervals greater than approximately 100 hr, precipitation intensity are typically lowest for evergreen needleleaf forests, while rainfall intensities tend to be highest for the cropland, grassland, and mixed forest catchments (Figure S9 in Supporting Information S1). This suggests that the low peak heights of stratified RRDs for evergreen needleleaf forests may be partly attributed to their relatively low precipitation intensity, rather than the effects of above- and below-ground forest characteristics alone. However, the precipitation intensity for cropland and grassland catchments is nearly identical to that for mixed forests across all recurrence intervals, but the peak heights of stratified RRDs in mixed forests are typically 26%–45% lower (Figures 2l, 2p, and 2t). This indicates that differences in precipitation intensity are unlikely to be the primary cause of the observed differences in peak runoff response across the four land cover types.

Compared to empirical methods that do not consider antecedent wetness, stratifying the RRDs by antecedent wetness conditions more effectively reveals the influence of forest cover on runoff response. However, this does not imply that total forest fraction or dominant land cover is the only factor explaining site-to-site differences in runoff response. Peak heights of stratified RRDs are more strongly associated with soil conductivity (Spearman $\rho = -0.30$, -0.46, and -0.41 for the three antecedent wetness ranges) than with forest cover fractions ($\rho = -0.23$, -0.38, and -0.28) (Figure S10 in Supporting Information S1; p-values all <0.001), but note that forests themselves also affect soil conductivity (see Section 3.4 below). Catchments with smaller areas, lower mean slopes, and lower geological permeability also tend to have greater RRD peak heights (Figure S9 in Supporting Information S1), but these correlations are weaker than those with forest cover or soil conductivity.

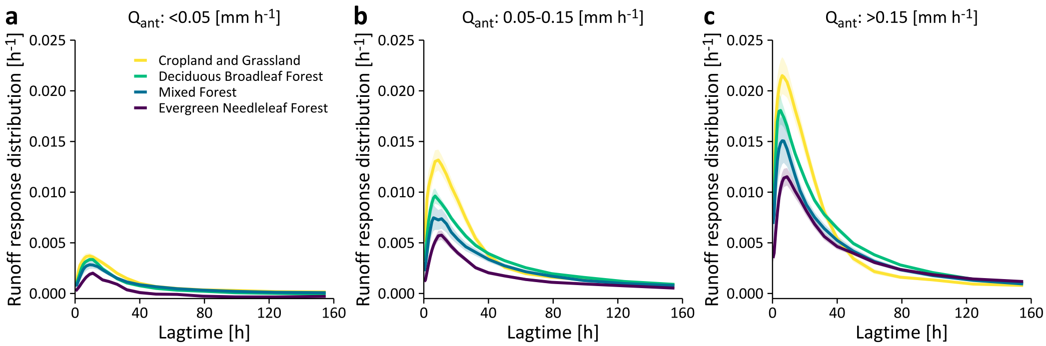

Figure 3. Runoff response distributions (RRDs) for the four dominant land cover types stratified by the three antecedent wetness conditions (Q_{ant}). (a–c) RRDs for the condition of $Q_{ant} < 0.05$, 0.05–0.15, and >0.15 mm hr^{-1}. For each antecedent wetness condition, each curve represents the average RRD across all catchments sharing a dominant land cover. Shaded areas indicate standard errors. For comparable antecedent wetness conditions, cropland and grassland catchments have the highest response peak height, followed by the deciduous broadleaf forest and mixed forest catchments. Evergreen needleleaf forest catchments have the lowest response peak height.

3.4. Potential Mechanisms of Forest Cover Effects on Runoff Response Peaks

Several mechanisms may cause forests to dampen runoff response peaks. First, forests tend to have more conductive soils because tree leaves, root systems (both living and dead), and soil fauna contribute to the development of soils that are rich in organic matter and have low bulk density, high macroporosity, and high saturated hydraulic conductivity (Greenwood & Buttle, 2014; Lozano-Baez et al., 2019; Neary et al., 2009, Figure S3 in Supporting Information S1 shows this also applies to our data set). The higher saturated hydraulic conductivity of forest soils enhances infiltration and reduces surface runoff (Germer et al., 2010; van Meerveld et al., 2021; Zimmermann et al., 2006, 2010). In addition, forest soils often have high water retention capacities (Bachmair et al., 2009; Neary et al., 2009; Pirastru et al., 2013). Greater soil water storage means that larger rainfall amounts are required to generate flood-producing runoff (Merz & Blöschl, 2003). For the same rainfall conditions, catchments with higher storage capacity thus tend to have lower peak flows.

Canopy storage and interception losses also reduce runoff (Floriancic et al., 2023; Keim et al., 2006; J. Liu et al., 2018). Interception losses result in the effective precipitation reaching the ground (and not lost to canopy or litter layer interception) being less than the "open rainfall" that is used in our analyses. This may help explain why the lowest response peak heights are observed for evergreen needleleaf forests (Figures 2 and 3), as they are known to have higher canopy interception losses than the other forest types, croplands, or grasslands (Grundmann et al., 2024; Miralles et al., 2010; Yue et al., 2021; C. Zheng & Jia, 2020; Zhong et al., 2022).

4. Conclusions

Our analysis demonstrates that land cover exerts a measurable and systematic influence on the peak runoff response once climatic effects are taken into account through the use of antecedent wetness classes (as quantified by antecedent streamflow). Across 252 U.S. catchments, we find that increasing forest cover is associated with lower runoff response peaks, with forested catchments exhibiting peak responses 16%–63% lower than those dominated by cropland or grassland under comparable wetness conditions. By largely disentangling land-cover effects from climate effects, our approach reveals the moderating (but not dominant) roles of forests on runoff peaks, which are often obscured in large-sample studies.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

The hourly precipitation and streamflow data were obtained from https://doi.org/10.5281/zenodo.4072701 (Gauch et al., 2020). The catchment static properties were obtained from https://zenodo.org/records/15529996 (Newman et al., 2022). The NDSI scripts are available from https://doi.org/10.16904/envidat.155 (Kirchner et al., 2020a). The ERRA script and introductory documentation for users are available from https://doi.org/10.16904/envidat.529 (Kirchner, 2024b), the relevant hydrological application of ERRA can be found in Kirchner (2024a), while the underlying mathematics of ERRA are described in Kirchner (2022). ERRA version 1.06 is used in this study. The parameter settings for the ERRA calculation and the data underlying our analysis are available at https://doi.org/10.5281/zenodo.18650855 (S. Liu, 2025).

Acknowledgments

This research was funded by the Swiss National Science Foundation (SNSF) (P500PN_230548).

References

Addor, N., Nearing, G., Prieto, C., Newman, A. J., Le Vine, N., & Clark, M. P. (2018). A ranking of hydrological signatures based on their predictability in space. *Water Resources Research*, *54*(11), 8792–8812. https://doi.org/10.1029/2018WR022606

Addor, N., Newman, A. J., Mizukami, N., & Clark, M. P. (2017). The CAMELS data set: Catchment attributes and meteorology for large-sample studies. *Hydrology and Earth System Sciences*, *21*(10), 5293–5313. https://doi.org/10.5194/hess-21-5293-2017

Alexander, P., Prestele, R., Verburg, P. H., Arneth, A., Baranzelli, C., Batista e Silva, F., et al. (2017). Assessing uncertainties in land cover projections. *Global Change Biology*, *23*(2), 767–781. https://doi.org/10.1111/gcb.13447

Anderson, B. J., Slater, L. J., Dadson, S. J., Blum, A. G., & Prosdocimi, I. (2022). Statistical attribution of the influence of urban and tree cover change on streamflow: A comparison of large sample statistical approaches. *Water Resources Research*, *58*(5), e2021WR030742. https://doi.org/10.1029/2021WR030742

Andréassian, V. (2004). Waters and forests: From historical controversy to scientific debate. *Journal of Hydrology*, *291*(1–2), 1–27. https://doi.org/10.1016/j.jhydrol.2003.12.015

Arora, V. K. (2002). The use of the aridity index to assess climate change effect on annual runoff. *Journal of Hydrology*, *265*(1–4), 164–177. https://doi.org/10.1016/S0022-1694(02)00101-4

Bachmair, S., Weiler, M., & Nützmann, G. (2009). Controls of land use and soil structure on water movement: Lessons for pollutant transfer through the unsaturated zone. *Journal of Hydrology*, *369*(3–4), 241–252. https://doi.org/10.1016/j.jhydrol.2009.02.031

Barnes, M. S., Bathurst, J. C., Lewis, E., & Quinn, P. F. (2023). Leaky dams augment afforestation to mitigate catchment scale flooding. *Hydrological Processes*, *37*(6), e14920. https://doi.org/10.1002/hyp.14920

Bathurst, J. C., Hagon, H., Barton, F. H., Iroumé, A., Kilbride, A., & Kilsby, C. (2022). Partial afforestation has uncertain effect on flood frequency and peak discharge at large catchment scales (100–1000 km^2), south-central Chile. *Hydrological Processes*, *36*(5), e14585. https://doi.org/10.1002/hyp.14585

Bathurst, J. C., Iroumé, A., Cisneros, F., Fallas, J., Iturraspe, R., Novillo, M. G., et al. (2011). Forest impact on floods due to extreme rainfall and snowmelt in four Latin American environments 1: Field data analysis. *Journal of Hydrology*, *400*(3–4), 281–291. https://doi.org/10.1016/j.jhydrol.2010.11.044

Berghuijs, W. R., Harrigan, S., Molnar, P., Slater, L. J., & Kirchner, J. W. (2019). The relative importance of different flood-generating mechanisms across Europe. *Water Resources Research*, *55*(6), 4582–4593. https://doi.org/10.1029/2019WR024841

Berghuijs, W. R., Sivapalan, M., Woods, R. A., & Savenije, H. H. G. (2014). Patterns of similarity of seasonal water balances: A window into streamflow variability over a range of time scales. *Water Resources Research*, *50*(7), 5638–5661. https://doi.org/10.1002/2014WR015692

Blöschl, G., Ardoin-Bardin, S., Bonell, M., Dorninger, M., Goodrich, D., Gutknecht, D., et al. (2007). At what scales do climate variability and land cover change impact on flooding and low flows? *Hydrological Processes*, *21*(9), 1241–1247. https://doi.org/10.1002/hyp.6669

Blum, A. G., Ferraro, P. J., Archfield, S. A., & Ryberg, K. R. (2020). Causal effect of impervious cover on annual flood magnitude for the United States. *Geophysical Research Letters*, *47*(5), e2019GL086480. https://doi.org/10.1029/2019GL086480

Brown, A. E., Western, A. W., McMahon, T. A., & Zhang, L. (2013). Impact of forest cover changes on annual streamflow and flow duration curves. *Journal of Hydrology*, *483*, 39–50. https://doi.org/10.1016/j.jhydrol.2012.12.031

Brown, A. E., Zhang, L., McMahon, T. A., Western, A. W., & Vertessy, R. A. (2005). A review of paired catchment studies for determining changes in water yield resulting from alterations in vegetation. *Journal of Hydrology*, *310*(1–4), 28–61. https://doi.org/10.1016/j.jhydrol.2004.12.010

Buechel, M., Slater, L., & Dadson, S. (2022). Hydrological impact of widespread afforestation in Great Britain using a large ensemble of modelled scenarios. *Communications Earth & Environment*, *3*(1), 6. https://doi.org/10.1038/s43247-021-00334-0

Coxon, G., McMillan, H., Bloomfield, J. P., Bolotin, L., Dean, J. F., Kelleher, C., et al. (2024). Wastewater discharges and urban land cover dominate urban hydrology signals across England and Wales. *Environmental Research Letters*, *19*(8), 084016. https://doi.org/10.1088/1748-9326/ad5bf2

Farley, K. A., Jobbágy, E. G., & Jackson, R. B. (2005). Effects of afforestation on water yield: A global synthesis with implications for policy. *Global Change Biology*, *11*(10), 1565–1576. https://doi.org/10.1111/j.1365-2486.2005.01011.x

Filoso, S., Bezerra, M. O., Weiss, K. C. B., & Palmer, M. A. (2017). Impacts of forest restoration on water yield: A systematic review. *PLoS One*, *12*(8), 1–26. https://doi.org/10.1371/journal.pone.0183210

Floriancic, M. G., Allen, S. T., Meier, R., Truniger, L., Kirchner, J. W., & Molnar, P. (2023). Potential for significant precipitation cycling by forest-floor litter and deadwood. *Ecohydrology*, *16*(2), e2493. https://doi.org/10.1002/eco.2493

Floriancic, M. G., Spies, D., van Meerveld, I. H. J., & Molnar, P. (2022). A multi-scale study of the dominant catchment characteristics impacting low-flow metrics. *Hydrological Processes*, *36*(1), e14462. https://doi.org/10.1002/hyp.14462

Gauch, M., Kratzert, F., Klotz, D., Nearing, G., Lin, J., & Hochreiter, S. (2020). Data for "rainfall-runoff prediction at multiple timescales with a single long short-term memory network" [Dataset]. *Zenodo*. https://doi.org/10.5281/zenodo.4072701

Germer, S., Neill, C., Krusche, A. V., & Elsenbeer, H. (2010). Influence of land-use change on near-surface hydrological processes: Undisturbed forest to pasture. *Journal of Hydrology*, *380*(3–4), 473–480. https://doi.org/10.1016/j.jhydrol.2009.11.022

Greenwood, W. J., & Buttle, J. M. (2014). Effects of reforestation on near-surface saturated hydraulic conductivity in a managed forest landscape, southern Ontario, Canada. *Ecohydrology*, *7*(1), 45–55. https://doi.org/10.1002/eco.1320

Grundmann, M. H., Molnar, P., & Floriancic, M. G. (2024). Quantification of enrichment processes in throughfall and stemflow in a mixed temperate forest. *Hydrological Processes*, *38*(7), e15224. https://doi.org/10.1002/hyp.15224

Hall, J., Scholl, M., Gorokhovich, Y., & Uriarte, M. (2022). Forest cover lessens the impact of drought on streamflow in Puerto Rico. *Hydrological Processes*, *36*(5), e14551. https://doi.org/10.1002/hyp.14551

Han, S., Slater, L., Wilby, R. L., & Faulkner, D. (2022). Contribution of urbanisation to non-stationary river flow in the UK. *Journal of Hydrology*, *613*, 128417. https://doi.org/10.1016/j.jhydrol.2022.128417

Jackson, R. B., Jobbágy, E. G., Avissar, R., Roy, S. B., Barrett, D. J., Cook, C. W., et al. (2005). Trading water for carbon with biological carbon sequestration. *Science*, *310*(5756), 1944–1947. https://doi.org/10.1126/science.1119282

James, A. L., & Roulet, N. T. (2009). Antecedent moisture conditions and catchment morphology as controls on spatial patterns of runoff generation in small forest catchments. *Journal of Hydrology*, *377*(3–4), 351–366. https://doi.org/10.1016/j.jhydrol.2009.08.039

Keim, R. F., Skaugset, A. E., & Weiler, M. (2006). Storage of water on vegetation under simulated rainfall of varying intensity. *Advances in Water Resources*, *29*(7), 974–986. https://doi.org/10.1016/j.advwatres.2005.07.017

Kirchner, J. W. (2009). Catchments as simple dynamical systems: Catchment characterization, rainfall-runoff modeling, and doing hydrology backward. *Water Resources Research*, *45*(2), W02429. https://doi.org/10.1029/2008WR006912

Kirchner, J. W. (2022). Impulse response functions for nonlinear, nonstationary, and heterogeneous systems, estimated by deconvolution and demixing of noisy time series. *Sensors*, *22*(9), 3291. https://doi.org/10.3390/s22093291

Kirchner, J. W. (2024a). Characterizing nonlinear, nonstationary, and heterogeneous hydrologic behavior using ensemble rainfall–runoff analysis (ERRA): Proof of concept. *Hydrology and Earth System Sciences*, *28*(19), 4427–4454. https://doi.org/10.5194/hess-28-4427-2024

Kirchner, J. W. (2024b). ERRA – An R script for ensemble rainfall–runoff analysis [Software]. *EnviDat*. https://doi.org/10.16904/envidat.529

Kirchner, J. W., Godsey, S. E., Solomon, M., Osterhuber, R., McConnell, J. R., & Penna, D. (2020a). *Daily cycles in solar flux, snowmelt, transpiration, groundwater, and streamflow at Sagehen and Independence Creeks, Sierra Nevada, USA [Collection]*. EnviDat. https://doi.org/10.16904/envidat.155

Kirchner, J. W., Godsey, S. E., Solomon, M., Osterhuber, R., McConnell, J. R., & Penna, D. (2020b). The pulse of a montane ecosystem: Coupled daily cycles in solar flux, snowmelt, transpiration, groundwater, and streamflow at Sagehen Creek and Independence Creek, Sierra Nevada, USA. *Hydrology and Earth System Sciences*, *24*(11), 5095–5123. https://doi.org/10.5194/hess-24-5095-2020

Krishnaswamy, J., Bonell, M., Venkatesh, B., Purandara, B. K., Lele, S., Kiran, M. C., et al. (2012). The rain–runoff response of tropical humid forest ecosystems to use and reforestation in the Western Ghats of India. *Journal of Hydrology*, *472*, 216–237. https://doi.org/10.1016/j.jhydrol.2012.09.016

Krishnaswamy, J., Bonell, M., Venkatesh, B., Purandara, B. K., Rakesh, K. N., Lele, S., et al. (2013). The groundwater recharge response and hydrologic services of tropical humid forest ecosystems to use and reforestation: Support for the "infiltration-evapotranspiration trade-off hypothesis". *Journal of Hydrology*, *498*, 191–209. https://doi.org/10.1016/j.jhydrol.2013.06.034

Lana-Renault, N., Nadal-Romero, E., Serrano-Muela, M. P., Alvera, B., Sánchez-Navarrete, P., Sanjuan, Y., & García-Ruiz, J. M. (2014). Comparative analysis of the response of various land covers to an exceptional rainfall event in the central Spanish Pyrenees, October 2012. *Earth Surface Processes and Landforms*, *39*(5), 581–592. https://doi.org/10.1002/esp.3465

Liu, J., Zhang, Z., & Zhang, M. (2018). Impacts of forest structure on precipitation interception and run-off generation in a semiarid region in northern China. *Hydrological Processes*, *32*(15), 2362–2376. https://doi.org/10.1002/hyp.13156

Liu, S. (2025). *Data supporting the analysis in the manuscript "Forest impacts on peak runoff revealed by accounting for the effects of climate" [Collection]*. Zenodo. https://doi.org/10.5281/zenodo.18650855

Liu, S., Seybold, H., van Meerveld, I., Wang, Y., & Kirchner, J. W. (2025). Tree planting and soil conservation measures have strongly attenuated storm runoff responses on the Chinese Loess Plateau. *Journal of Hydrology*, *662*, 134039. https://doi.org/10.1016/j.jhydrol.2025.134039

Lozano-Baez, S. E., Cooper, M., Meli, P., Ferraz, S. F., Rodrigues, R. R., & Sauer, T. J. (2019). Land restoration by tree planting in the tropics and subtropics improves soil infiltration, but some critical gaps still hinder conclusive results. *Forest Ecology and Management*, *444*, 89–95. https://doi.org/10.1016/j.foreco.2019.04.046

McEachran, Z. P., Reese, G. C., Karwan, D. L., Slesak, R. A., & Vogeler, J. (2023). Effects of forest disturbance on water yield and peak flow in low-relief glaciated catchments assessed with Bayesian parameter estimation. *Hydrological Processes*, *37*(8), e14956. https://doi.org/10.1002/hyp.14956

Merz, R., & Blöschl, G. (2003). A process typology of regional floods. *Water Resources Research*, *39*(12), 1340. https://doi.org/10.1029/2002WR001952

Miralles, D. G., Gash, J. H., Holmes, T. R. H., de Jeu, R. A. M., & Dolman, A. J. (2010). Global canopy interception from satellite observations. *Journal of Geophysical Research*, *115*(D16), D16122. https://doi.org/10.1029/2009JD013530

Neary, D. G., Ice, G. G., & Jackson, C. R. (2009). Linkages between forest soils and water quality and quantity. *Forest Ecology and Management*, *258*(10), 2269–2281. https://doi.org/10.1016/j.foreco.2009.05.027

Newman, A. J., Clark, M. P., Sampson, K., Wood, A., Hay, L. E., Bock, A., et al. (2015). Development of a large-sample watershed-scale hydrometeorological data set for the contiguous USA: Data set characteristics and assessment of regional variability in hydrologic model performance. *Hydrology and Earth System Sciences*, *19*(1), 209–223. https://doi.org/10.5194/hess-19-209-2015

Newman, A. J., Sampson, K., Clark, M., Bock, A., Viger, R., Blodgett, D., et al. (2022). CAMELS: Catchment attributes and MEteorology for Large-sample studies (1.2) [Dataset]. *Zenodo*. https://doi.org/10.5065/D6MW2F4D

Ogden, F. L., Crouch, T. D., Stallard, R. F., & Hall, J. S. (2013). Effect of land cover and use on dry season river runoff, runoff efficiency, and peak storm runoff in the seasonal tropics of central Panama. *Water Resources Research*, *49*(12), 8443–8462. https://doi.org/10.1002/2013WR013956

Padrón, R. S., Gudmundsson, L., Greve, P., & Seneviratne, S. I. (2017). Large-scale controls of the surface water balance over land: Insights from a systematic review and meta-analysis. *Water Resources Research*, *53*(11), 9659–9678. https://doi.org/10.1002/2017WR021215

Pirastru, M., Castellini, M., Giadrossich, F., & Niedda, M. (2013). Comparing the hydraulic properties of forested and grassed soils on an experimental hillslope in a Mediterranean environment. *Procedia Environmental Sciences*, *19*, 341–350. https://doi.org/10.1016/j.proenv.2013.06.039

Price, K., Jackson, C. R., & Parker, A. J. (2010). Variation of surficial soil hydraulic properties across land uses in the southern Blue Ridge Mountains, North Carolina, USA. *Journal of Hydrology*, *383*(3–4), 256–268. https://doi.org/10.1016/j.jhydrol.2009.12.041

Rogger, M., Agnoletti, M., Alaoui, A., Bathurst, J. C., Bodner, G., Borga, M., et al. (2017). Land use change impacts on floods at the catchment scale: Challenges and opportunities for future research. *Water Resources Research*, *53*(7), 5209–5219. https://doi.org/10.1002/2017WR020723

Salazar, S., Francés, F., Komma, J., Blume, T., Francke, T., Bronstert, A., & Blöschl, G. (2012). A comparative analysis of the effectiveness of flood management measures based on the concept of "retaining water in the landscape" in different European hydro-climatic regions. *Natural Hazards and Earth System Sciences*, *12*(11), 3287–3306. https://doi.org/10.5194/nhess-12-3287-2012

Silveira, L., & Alonso, J. (2009). Runoff modifications due to the conversion of natural grasslands to forests in a large basin in Uruguay. *Hydrological Processes*, *23*(2), 320–329. https://doi.org/10.1002/hyp.7156

Slater, L., Coxon, G., Brunner, M., McMillan, H., Yu, L., Zheng, Y., et al. (2024). Spatial sensitivity of river flooding to changes in climate and land cover through explainable AI. *Earth's Future*, *12*(5), e2023EF004035. https://doi.org/10.1029/2023EF004035

Song, X. P., Hansen, M. C., Stehman, S. V., Potapov, P. V., Tyukavina, A., Vermote, E. F., & Townshend, J. R. (2018). Global land change from 1982 to 2016. *Nature*, *560*(7720), 639–643. https://doi.org/10.1038/s41586-018-0411-9

Stein, L., Clark, M. P., Knoben, W. J. M., Pianosi, F., & Woods, R. A. (2021). How do climate and catchment attributes influence flood generating processes? A large-sample study for 671 catchments across the contiguous USA. *Water Resources Research*, *57*(4), e2020WR028300. https://doi.org/10.1029/2020WR028300

Stratford, C., House, A., Old, G., Acreman, M., Dueñas-Lopez, M. A., Miller, J., et al. (2017). *Do trees in UK-relevant river catchments influence fluvial flood peaks? Wallingford, UK*. (CEH Project no. NEC06063) (Vol. 46). NERC/Centre for Ecology & Hydrology.

Tarasova, L., Basso, S., Zink, M., & Merz, R. (2018). Exploring controls on rainfall-runoff events: 1. Time series-based event separation and temporal dynamics of event runoff response in Germany. *Water Resources Research*, *54*(10), 7711–7732. https://doi.org/10.1029/2018WR022587

United States Geological Survey. (2021). USGS instantaneous values web service. Retrieved from https://waterservices.usgs.gov/rest/IV-Service.html

van Meerveld, H. J., Jones, J. P. G., Ghimire, C. P., Zwartendijk, B. W., Lahitiana, J., Ravelona, M., & Mulligan, M. (2021). Forest regeneration can positively contribute to local hydrological ecosystem services: Implications for forest landscape restoration. *Journal of Applied Ecology*, *58*(4), 755–765. https://doi.org/10.1111/1365-2664.13836

van Meerveld, H. J., Zhang, J., Tripoli, R., & Bruijnzeel, L. A. (2019). Effects of reforestation of a degraded Imperata grassland on dominant flow pathways and streamflow responses in Leyte, the Philippines. *Water Resources Research*, *55*(5), 4128–4148. https://doi.org/10.1029/2018WR023896

Winkler, K., Fuchs, R., Rounsevell, M., & Herold, M. (2021). Global land use changes are four times greater than previously estimated. *Nature Communications*, *12*(1), 2501. https://doi.org/10.1038/s41467-021-22702-2

Xia, Y., Mitchell, K., Ek, M., Sheffield, J., Cosgrove, B., Wood, E., et al. (2012). Continental-scale water and energy flux analysis and validation for the North American land data assimilation system project phase 2 (NLDAS-2): 1. Intercomparison and application of model products. *Journal of Geophysical Research*, *117*(D3), D03109. https://doi.org/10.1029/2011JD016048

Yue, K., De Frenne, P., Fornara, D. A., Van Meerbeek, K., Li, W., Peng, X., et al. (2021). Global patterns and drivers of rainfall partitioning by trees and shrubs. *Global Change Biology*, *27*(14), 3350–3357. https://doi.org/10.1111/gcb.15644

Zhang, L., Zhao, F. F., & Brown, A. E. (2012). Predicting effects of plantation expansion on streamflow regime for catchments in Australia. *Hydrology and Earth System Sciences*, *16*(7), 2109–2121. https://doi.org/10.5194/hess-16-2109-2012

Zhang, M., Liu, N., Harper, R., Li, Q., Liu, K., Wei, X., et al. (2017). A global review on hydrological responses to forest change across multiple spatial scales: Importance of scale, climate, forest type and hydrological regime. *Journal of Hydrology*, *546*, 44–59. https://doi.org/10.1016/j.jhydrol.2016.12.040

Zheng, C., & Jia, L. (2020). Global canopy rainfall interception loss derived from satellite Earth observations. *Ecohydrology*, *13*(2), e2186. https://doi.org/10.1002/eco.2186

Zheng, Y., Coxon, G., Woods, R., Li, J., & Feng, P. (2023). Controls on the spatial and temporal patterns of rainfall-runoff event characteristics—A large sample of catchments across Great Britain. *Water Resources Research*, *59*(6), e2022WR033226. https://doi.org/10.1029/2022WR033226

Zhong, F., Jiang, S., van Dijk, A. I. J. M., Ren, L., Schellekens, J., & Miralles, D. G. (2022). Revisiting large-scale interception patterns constrained by a synthesis of global experimental data. *Hydrology and Earth System Sciences*, *26*(21), 5647–5667. https://doi.org/10.5194/hess-26-5647-2022

Zimmermann, B., Elsenbeer, H., & De Moraes, J. M. (2006). The influence of land-use changes on soil hydraulic properties: Implications for runoff generation. *Forest Ecology and Management*, *222*(1–3), 29–38. https://doi.org/10.1016/j.foreco.2005.10.070

Zimmermann, B., Papritz, A., & Elsenbeer, H. (2010). Asymmetric response to disturbance and recovery: Changes of soil permeability under forest-pasture-forest transitions. *Geoderma*, *159*(1–2), 209–215. https://doi.org/10.1016/j.geoderma.2010.07.013