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Runoff thresholds as state-dependent connectivity transitions: A global synthesis across diverse catchments

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Key Points:

- Runoff thresholds are primarily driven by state-dependent hydrologic connectivity, rather than fixed rainfall exceedances.
- Dominant runoff mechanisms evolve with increasing wetness, typically transitioning from surface- to subsurface- and groundwater-dominated pathways.
- Recurrent soil–geology combinations create transferable structural fingerprints that govern threshold behavior and mechanism transitions.

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Abstract

Runoff threshold behavior is widely reported in event-based hydrological studies, but its interpretation and cross-catchment comparability remain unresolved due to variations in threshold metrics and values across climates, landscape structures, and observational focuses. This study synthesizes reported storm-runoff thresholds from experimental catchments worldwide by compiling the indicators used to detect nonlinearity, the dominant runoff generation mechanisms, their observed transition pathways under increasing wetness, and recurrent soil–geology fingerprints. Across mechanisms and climates, thresholds are identified using diverse (and often non-standardized) rainfall-based, state-based, and composite indicators. However, antecedent and within-event state variables (e.g., soil moisture, catchment storage, groundwater level) consistently provide better explanations for nonlinear runoff responses than rainfall metrics alone, indicating that threshold behavior is primarily controlled by the state of the catchment but is triggered by rainfall. Subsurface- and saturation-related mechanisms dominate the reported cases, particularly in humid environments. When mechanism shifts are explicitly documented, responses show a strong directional organization with increasing wetness, typically evolving from infiltration-excess overland flow to saturation-excess overland flow, and then to subsurface or groundwater-dominated pathways. Soil–geology network analysis further reveals that each dominant mechanism is associated with recurring combinations of soil depth, texture, permeability contrasts, lithology, and geological structure, forming structural fingerprints that regulate ~~connectivity~~ development. Overall, runoff thresholds are best understood as markers of hydrologic connectivity transitions within structurally constrained landscapes, rather than fixed rainfall exceedances. We propose a connectivity-based conceptual framework linking rainfall forcing, evolving states, structural controls, and mechanism transitions to support cross-catchment comparison, guide future observations, and improve the representation of nonlinear runoff responses in hydrological models.

Keywords: Runoff thresholds; Hydrologic connectivity; Soil–geology controls; Transition

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1. Introduction

Storm runoff generation often exhibits strong nonlinearity and threshold behavior, where small changes in rainfall or antecedent wetness can trigger disproportionate increases in runoff. Numerous event-based studies have shown that similar storms may generate vastly different runoff outcomes depending on catchment wetness, storage conditions, ~~and subsurface flow activation~~ (Blume and Van Meerveld, 2015; Penna et al., 2011; Sidle et al., 2000; Tromp-van Meerveld and McDonnell, 2006a). This nonlinear behavior challenges traditional interpretations based on rainfall magnitude, ~~highlighting the state-dependent nature of storm runoff, with rainfall merely acting as a trigger.~~

Subsequent advances shifted focus from fixed rainfall thresholds to state-dependent activation of hydrologic connectivity. Fill-and-spill concepts emphasized the episodic activation and coupling of subsurface and depressional storage once critical wetness thresholds are exceeded (Green and Crumpton, 2023; Jehn et al., 2021; McDonnell, 2013), ~~while h~~ydrologic connectivity theory framed runoff response as an emergent outcome of progressively coupled hillslopes, soils, groundwater, and channels (Blume and Meerveld, 2015; Fu et al., 2013; McDonnell, 2013). Connectivity- and storage-based frameworks ~~further demonstrated~~ that threshold-like runoff behavior emerges when incremental rainfall leads to disproportionate increases in internal hydrologic connectivity and flow transmission (Ares et al., 2020; von Freyberg et al., 2014; McGuire and McDonnell, 2010; Wilson et al., 2017; Zimmermann et al., 2014). ~~Despite these advances, the question remains: why do similar storms generate fundamentally different runoff responses across events and catchments?~~

Despite conceptual progress, challenges remain in synthesizing storm runoff nonlinearity across catchments. Threshold behavior ~~— marked by abrupt runoff increases or shifts in dominant flow pathways —~~ has been robustly documented for infiltration-excess overland flow (Deng et al., 2024; Kampf et al., 2018; Lana-Renault et al., 2013; Ross et al., 2021)), saturation-excess overland flow(Mentzafou et al., 2023; Ross et al., 2021; Steenhuis et al., 2013; Wang et al., 2022b), subsurface stormflow (Kirchner, 2024; Lee and Kim, 2020; Sidle et al., 2000; Wang et al., 2022a), and shallow groundwater-dominated responses (Cui et al., 2024; Gao et al., 2024; Graeff et al., 2009; Scaife et al., 2020). However, while threshold responses are well recognized, a comprehensive cross-mechanism synthesis explaining how differences in storage states,

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connectivity structures, and dominant pathways lead to contrasting runoff responses under similar storm conditions remains lacking.

Recent comparative studies often focus on whether specific runoff generation mechanisms occur under particular climatic or landscape conditions (McMillan et al., 2025), or on statistical associations between climate, vegetation, and runoff behavior (Chappell et al., 2017; Douinot et al., 2022; Lana-Renault et al., 2013; Mirus and Loague, 2013; Steenhuis et al., 2013). While such studies have advanced our understanding of dominant mechanisms and climatic controls, three key gaps remain. First, dominant runoff mechanisms are often treated as static catchment attributes, yet evidence shows that multiple mechanisms can coexist and shift dynamically with antecedent wetness and event progression (Cain et al., 2022; Martínez-Carreras et al., 2016; Penna et al., 2011; Ruggenthaler et al., 2015; Saffarpour et al., 2016; Sidle et al., 2000). Few studies have examined how these mechanisms transition across wetness gradients in a cross-catchment framework. Second, runoff thresholds are identified using heterogeneous indicators—ranging from rainfall metrics to soil moisture, storage, groundwater level, and composite indices—but it remains unclear under which conditions these indicators are comparable or transferable across catchments (Mirus and Loague, 2013; Scaife et al., 2020). Third, although soil and geological properties are widely acknowledged as fundamental controls on runoff generation, their influence is often discussed qualitatively, with few studies quantitatively assessing whether distinct runoff mechanisms are associated with recurring soil–geological attributes that form structural "fingerprints" governing connectivity development (James and Roulet, 2007; McGuire and McDonnell, 2010; Mirus and Loague, 2013; Scaife et al., 2020).

These limitations hinder a unified, process-oriented understanding of runoff threshold behavior across catchments. While many studies have examined threshold responses or described runoff generation mechanisms, the explicit integration of threshold indicators, dominant mechanisms, their transitions, and soil–geological context remains rare. To address these gaps, this study conducts a global synthesis of nonlinear and threshold storm runoff behavior across a large set of experimental catchments from arid to humid regions. Rather than focusing solely on mechanism occurrence or isolated threshold metrics, we explicitly link threshold indicators, dominant runoff generation mechanisms, their dynamic transitions, and soil–geological context within a unified analytical framework.

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Specifically, we address the following questions:

1. Is there a transferable rainfall–wetness indicator that consistently captures storm runoff regime shifts beyond rainfall-only metrics?

2. Do dominant runoff generation mechanisms follow systematic and directional evolution pathways as catchment wetness increases?

3. Do observed mechanism transitions reflect a coherent pattern of progressively strengthening hydrologic connectivity?

4. Are runoff mechanisms associated with recurrent soil–geological combinations that systematically shape connectivity development and threshold behavior?

By integrating event-scale thresholds with mechanism dynamics, connectivity evolution, and structural context, this study aims to advance a process-based and connectivity-oriented interpretation of runoff thresholds. Rather than seeking universal threshold values, which vary across catchments, we focus on recurring trigger–state–structure combinations that govern nonlinear runoff responses across diverse hydrological settings.

~~These limitations hinder a unified, process-oriented understanding of runoff threshold behavior across catchments. Despite numerous studies examining threshold responses and runoff generation mechanisms, the integration of threshold indicators, dominant mechanisms, their transitions, and the soil geological context remains rare. To address these gaps, this study conducts a global synthesis of nonlinear and threshold storm runoff behavior across a large set of well-instrumented experimental catchments, spanning arid to humid regions. Rather than focusing solely on mechanism occurrence or isolated threshold metrics, we explicitly link threshold indicators, dominant runoff mechanisms, their dynamic transitions, and soil–geological context within a unified analytical framework.~~

2. Data and Methods

2.1 Literature synthesis and catchment database

To systematically investigate nonlinear and threshold-driven runoff generation under storm conditions, we conducted a comprehensive synthesis of the international literature on rainfall–runoff nonlinearity, ~~abrupt hydrological response shifts,~~ and runoff threshold behavior. The

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review targeted experimental, observational, and process-based studies that explicitly examined stormflow generation processes across a wide range of climatic and physiographic settings.

We searched peer-reviewed literature using Web of Science Core Collection and Scopus, supplemented by Google Scholar for catchment-specific follow-up, to identify studies reporting event-scale nonlinear or threshold storm-runoff behavior. The search combined terms related to nonlinearity, thresholds, and runoff generation, including "runoff threshold," "threshold behavior," "nonlinear runoff," "rainfall-runoff nonlinearity," and "stormflow generation." These terms were applied to the full text of articles, not just titles, ensuring a comprehensive search. Over 200 articles were initially screened based on title/abstract and full text.

Studies were retained if they: (i) provided well-documented storm-event observations ~~(e.g., rainfall and runoff time series, hydrograph/hysteresis analyses, soil moisture or groundwater dynamics, tracers/isotopes, or similar process evidence),~~ and (ii) included an explicit interpretation of nonlinear or threshold-like runoff behavior, along with the associated dominant runoff generation mechanism(s). Studies focusing solely on linear rainfall-runoff relationships or long-term water balance analyses, without event-scale threshold interpretation, were excluded. Each study was thoroughly reviewed to ensure it met these criteria. We extracted data for 176 catchments from the screened literature~~–~~. Thirty-nine ~~catchments~~ based solely on model simulations, without direct field observations, were excluded. The final dataset includes 138 catchments (shown in Fig. 1 and Table A1)from humid, semi-humid, semi-arid, and ~~one~~ arid climate, span~~ning~~ diverse vegetation, soil, and geological settings, providing broad hydroclimatic coverage ~~while maintaining a focus on event-scale runoff processes and nonlinear behavior~~ .

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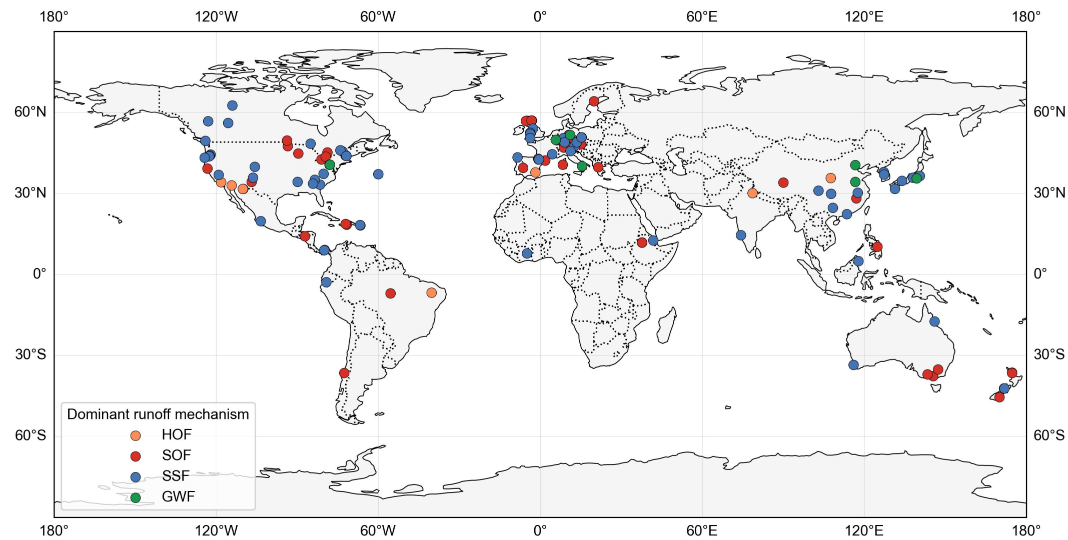

Figure 1. Global distribution of study catchments categorized by dominant runoff generation mechanisms. Colored symbols indicate the dominant or combined runoff generation mechanisms reported for each catchment, including infiltration-excess overland flow (HOF), saturation-excess overland flow (SOF), subsurface stormflow (SSF), groundwater-dominated flow (GWF), and their combinations.

~~Catchments were classified based on the dominant or combined runoff mechanisms reported in the original studies, including HOF, SOF, SSF, GWF, and their combinations. GWF refers to shallow groundwater responses within weathered bedrock or fractured regolith that contribute to event-scale stormflow, not regional confined aquifers responsible for long-term baseflow.~~

For each catchment, we extracted information on:

(i) Aridity ~~category~~ and vegetation type;

(ii) Soil properties, including depth, texture, and permeability;

(iii) Geological and hydrogeological characteristics; and

(iv) Reported dominant runoff generation mechanisms, along with the state variables and indicators used to identify nonlinear or threshold runoff behavior.

2.2 Classification of runoff generation mechanisms

Runoff generation mechanisms were classified based on established process-based frameworks that distinguish surface- and subsurface-dominated stormflow pathways. Each

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catchment was assigned one or more dominant mechanisms, such as HOF, SOF, SSF, and GWF, based on reported stormflow responses. GWF refers to shallow groundwater responses within weathered bedrock or fractured regolith, contributing to event-scale stormflow rather than long-term baseflow.

Classification reflects the mechanism that primarily controls stormflow during events exhibiting nonlinear or threshold behavior. Dominance refers to the mechanism contributing most strongly to runoff generation once threshold conditions are exceeded, rather than implying exclusive operation of a single process. Where studies reported multiple coexisting or sequentially activated mechanisms, composite categories (e.g., HOF + SOF, SOF + SSF, SSF + GWF) were used

Mechanism assignments were strictly based on process-based evidence from the original studies, such as hydrograph characteristics, runoff coefficients, soil moisture and groundwater dynamics, tracer/isotope observations, and shifts in flow pathways. No reinterpretation of the original authors' conclusions was applied.

2.3 Definition of runoff regime shifts and threshold conditions

Runoff regime shifts are defined as abrupt, nonlinear changes in stormflow response that reflect transitions in dominant runoff generation processes or hydrological connectivity, rather than proportional increases in rainfall input alone. A regime shift was identified when one or more of the following conditions were reported during storm events:

(i) a distinct breakpoint in the rainfall–runoff relationship;

(ii) a disproportionate increase in runoff relative to rainfall input;

(iii) a documented transition in dominant runoff generation mechanism; or

(iv) enhanced hydrological connectivity, such as hillslope–channel coupling, activation of soil–bedrock interfaces, or rapid groundwater table rise.

Threshold behavior was interpreted as the joint outcome of event-scale rainfall forcing and catchment hydrological state. Accordingly, rainfall characteristics (e.g., amount, intensity, duration) were treated as triggering conditions, while antecedent and within-event state variables—commonly antecedent soil water content (ASW), antecedent moisture condition (AMC), soil water content (SWC), and groundwater level (GWL)—were used as indicators modulating the emergence of nonlinear responses. Structural catchment properties (e.g., soil

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texture and depth, permeability contrasts, bedrock characteristics) were not treated as threshold indicators but as longer-term controls shaping dominant runoff mechanisms, and were analyzed separately in Section 3.5.

2.4 Climate and vegetation classification

Catchments were grouped by climatic wetness and dominant vegetation type to assess how dominant runoff generation mechanisms and regime shifts vary across environmental gradients. These classifications provide contextual interpretation of mechanism occurrence and transition patterns, not as direct explanatory variables

Climatic wetness was classified into humid, semi-humid, semi-arid, and arid categories based on climate-type descriptions and mean annual precipitation from the source studies. As potential evapotranspiration data was rarely available, a uniform aridity index (AI = P/PET) was not calculated. Instead, classification combined Köppen climate data (where available) with reported precipitation ranges and qualitative aridity descriptions for consistent cross-catchment categorization. Vegetation types were classified as forest, grassland, cropland, shrubland, or mixed vegetation based on study descriptions.

2.5 Soil–geology keyword co-occurrence network

To examine recurring associations between dominant runoff generation mechanisms and subsurface characteristics, we conducted a soil–geology keyword co-occurrence network analysis. This analysis identifies combinations of soil and geological attributes that frequently co-occur with specific runoff mechanisms across catchments.

For each catchment, soil- and geology-related descriptors from the literature were extracted and standardized into a consistent keyword set, including soil depth, texture, permeability, bedrock type, and structural features like fracturing. Only attributes explicitly linked to runoff generation (e.g., soil depth, texture, permeability contrasts, lithology) were included. Implicit interpretations or inferred characteristics not directly reported were excluded to minimize subjectivity.

To ensure consistency across studies, extracted descriptors were standardized using a synonym normalization table (Table S2), which merged similar terms into unified descriptors (e.g., “shallow regolith,” “thin soils,” and “shallow soils” were combined as “shallow soil”). This normalization focused on preserving the hydrological meaning while reducing linguistic

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variability. Keyword extraction and standardization were independently reviewed by two researchers to ensure consistency. Discrepancies were resolved through discussion and reference to original study descriptions.

The resulting standardized set of descriptors was used to construct soil–geology co-occurrence networks, linking dominant runoff generation mechanisms to recurring soil and geological attributes across catchments. In these networks, nodes represent individual soil or geological keywords, and edges represent their co-occurrence within the same catchment. To increase robustness and reduce the influence of isolated case studies, only descriptor pairs occurring in at least two independent catchments were retained. Edge thickness reflects the frequency of co-occurrence and was used to identify dominant soil–geology associations for each runoff generation mechanism. Sensitivity tests with stricter co-occurrence thresholds (≥3 catchments) showed similar structural clusters, indicating that the identified fingerprints are not driven by isolated cases.

3. Results

3.1 Reported state variables and indicators of runoff threshold behavior

This section summarizes how nonlinear runoff threshold behavior has been reported in the reviewed literature, focusing on the state variables and indicators used, rather than on process interpretation.

The global distribution of the reviewed catchments and their reported dominant runoff generation mechanisms is shown in Fig. 1. To facilitate comparison across mechanisms, Fig. 2 synthesizes state variables and threshold indicators for four dominant runoff generation mechanisms—HOF, SOF, SSF, and GWF—excluding composite mechanisms. In Fig. 2, dominant runoff mechanisms are linked to reported state variables and indicators of nonlinear runoff behavior. The width of each flow represents the number of studies reporting a given mechanism–variable or mechanism–indicator combination.

A wide range of state variables has been used to characterize hydrological conditions associated with nonlinear runoff responses. These include antecedent soil moisture, antecedent moisture condition, soil or catchment storage state, groundwater level, and coupled soil–

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groundwater metrics. The relative frequency of these variables varies among dominant runoff mechanisms, as illustrated in Fig. 2.

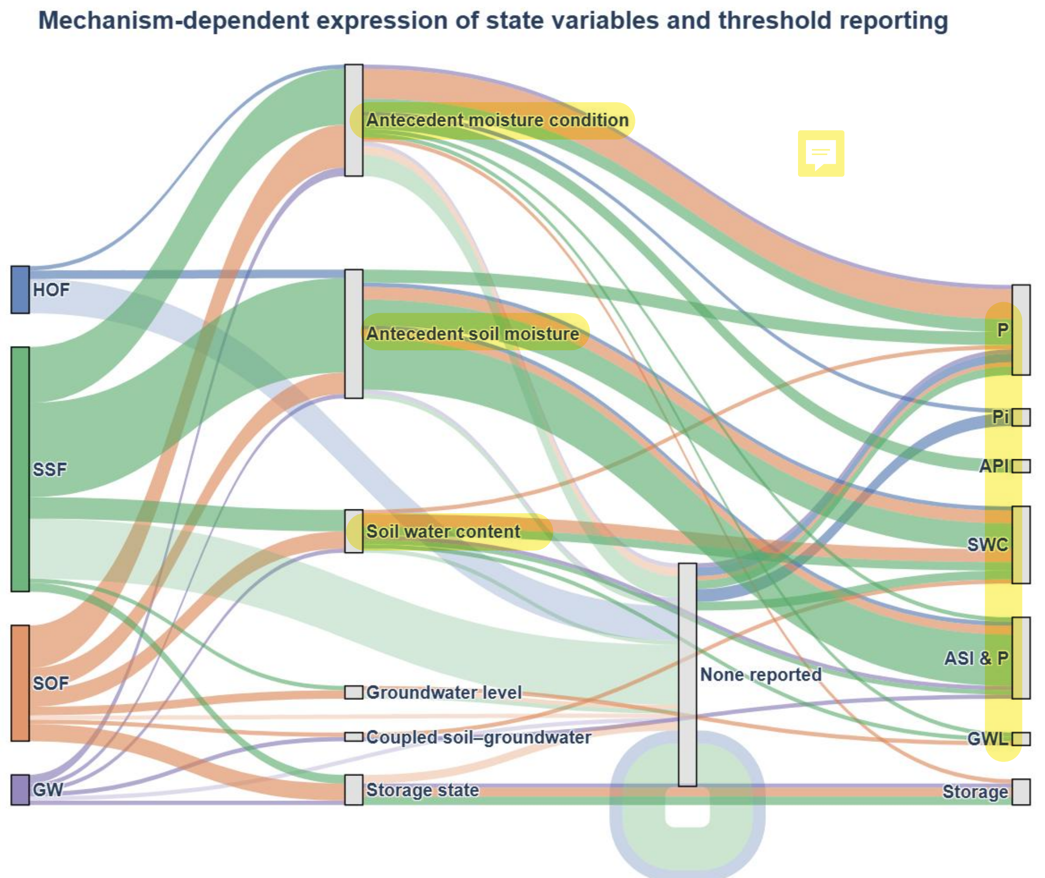

Figure 2. Sankey diagram summarizing reported trigger–state indicators used to identify nonlinear runoff threshold behavior across dominant runoff generation mechanisms. Nodes on the left represent dominant runoff mechanisms, the middle nodes represent state variables, and the right nodes represent indicators used to identify threshold behavior. Flow bands connect mechanisms, state variables, and indicators, with band width proportional to the number of studies reporting each combination. The node "None reported" indicates studies that described nonlinear runoff responses without specifying an explicit threshold indicator.

Indicators used to identify nonlinear runoff behavior also differ substantially across studies. These include rainfall-based variables such as total event rainfall and rainfall intensity; state-based variables like soil water content, groundwater level, or storage metrics; and composite indicators combining rainfall and antecedent wetness information. In some studies, no explicit

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quantitative indicator of nonlinear behavior was reported, with threshold behavior identified qualitatively.

Distinct reporting patterns emerge across mechanisms. Studies classified as HOF-dominated more frequently report rainfall-based indicators, whereas studies dominated by SOF, SSF, and GWF tend to report antecedent wetness, storage-related variables, or groundwater conditions. Composite indicators are reported across multiple mechanisms. ~~Overall, Fig. 2 highlights substantial variability in the variables and indicators used to characterize runoff threshold behavior.~~

3.2 Frequency and proportional contribution of dominant runoff generation mechanisms

Figure 3 summarizes the absolute frequency ~~and relative contribution~~ of dominant runoff generation mechanisms across the reviewed catchments. ~~Panel (a) shows the number of catchments associated with each mechanism, while panel (b) presents their proportional contribution to the dataset.~~ Across all reviewed studies, ~~subsurface-related mechanisms are more frequently reported.~~ SSF is the most common mechanism, accounting for 41~~.0~~% of all catchments, followed by combined SOF–SSF mechanisms (20~~.9~~%) and SOF alone (19~~.4~~%). ~~Together, SSF, SOF, and their combinations represent the majority of reported cases.~~

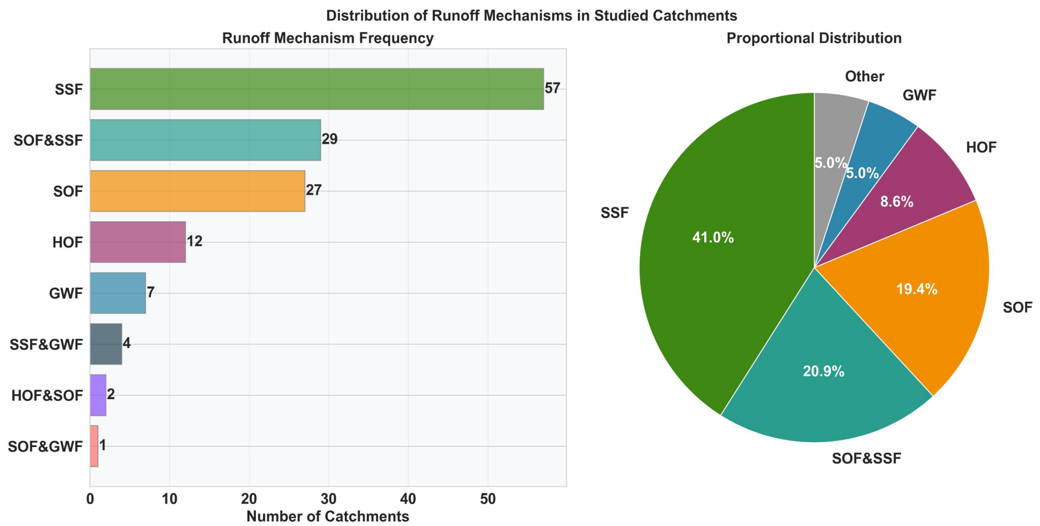

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Figure 3. Frequency and ~~proportional contribution~~ of dominant runoff generation mechanisms reported in the reviewed ~~catchments.~~ The left panel shows the number of catchments classified under each dominant runoff mechanism or reported mechanism combination, based on the primary interpretation in the original studies. The right panel illustrates the proportional contribution of each mechanism category to the overall dataset.

In contrast, HOF accounts for less than 10% of the reviewed catchments. GWF and categories involving groundwater represent a smaller fraction of the dataset.

3.3 Aridity- and vegetation-specific partitioning of dominant runoff generation mechanisms

Figure 4 summarizes the distribution of reported dominant runoff generation mechanisms across aridity and vegetation categories. Stacked bar charts show the number of catchments with each dominant mechanism within four aridity classes (humid, semi-humid, semi-arid, and arid) and across major vegetation types. Single and combined mechanisms are shown separately.

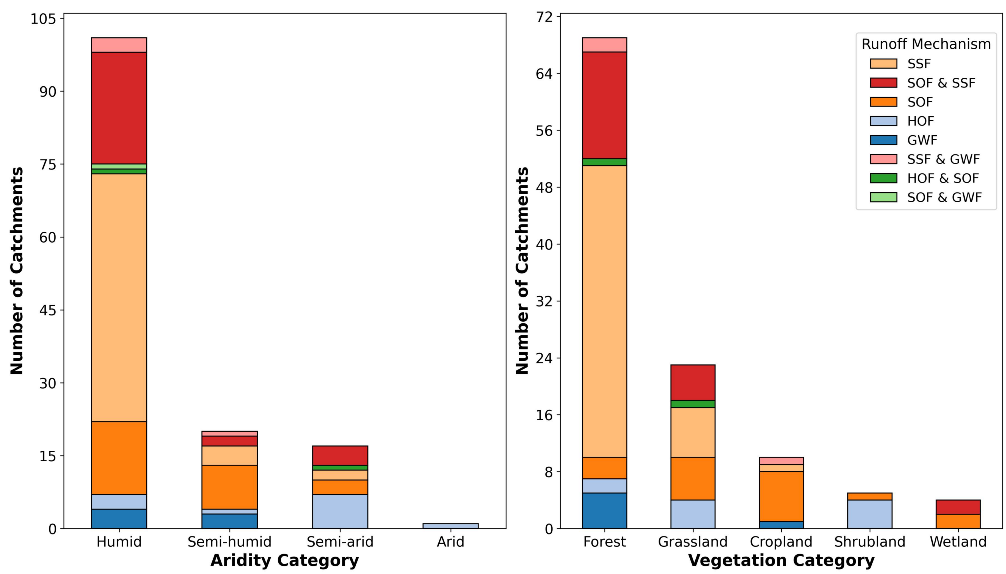

Figure 4. Distribution of dominant runoff generation mechanisms across aridity and vegetation categories.

~~Across the aridity gradient (Fig. 4a),~~ humid catchments ~~account for the majority of observations and~~ exhibit the widest range of reported runoff generation mechanisms. SSF represents the largest share, followed by SOF and combined SOF–SSF mechanisms. Groundwater-related mechanisms (GWF and SSF–GWF) are almost exclusively reported in humid catchments. Semi-humid catchments are ~~fewer and~~ are dominated by SOF, with additional

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contributions from SSF and GWF. In semi-arid catchments, the total number of reported systems is smaller; SSF and SOF remain, but HOF constitutes a larger proportion relative to wetter classes. Only one arid catchment is included, classified as HOF-dominated.

Mechanism distributions also vary across vegetation types (Fig. 4b). Forested catchments are the most frequent, representing a mix of SSF, SOF, SOF–SSF combinations, and groundwater-related mechanisms. Grassland catchments show a mixture of SSF, SOF, and HOF. Cropland catchments, less frequently reported, are mainly associated with SOF. Shrubland and wetland catchments are underrepresented; shrubland catchments are mostly HOF-dominated, while wetland catchments are mostly SOF and SOF–SSF.

Figure 5 further summarizes the aridity composition of the five most frequently reported dominant runoff generation mechanisms (SSF, SOF–SSF, SOF, HOF, and GWF), expressed as percentages relative to the total number of catchments reporting each mechanism.

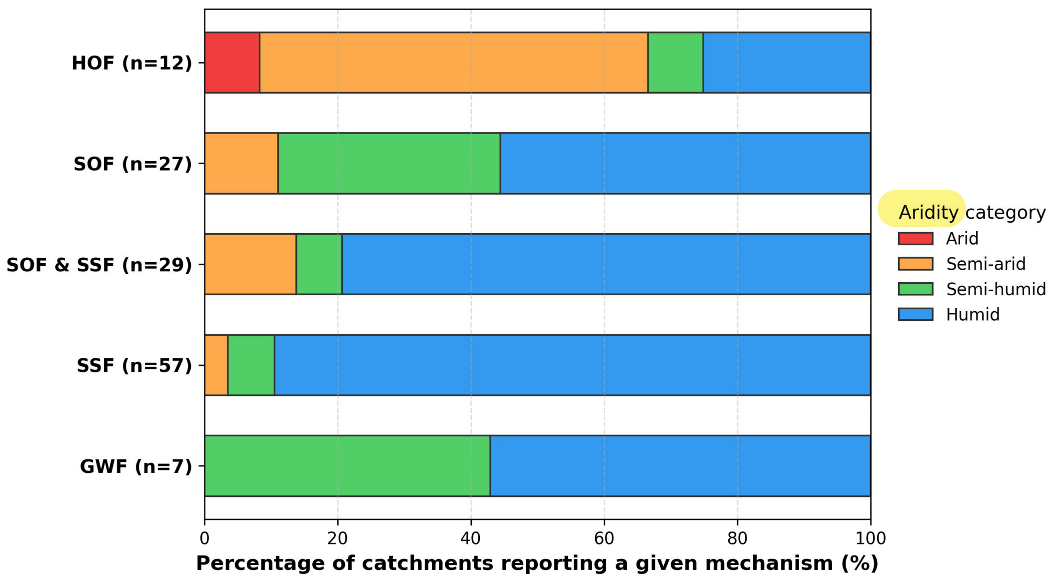

Figure 5. Climatic composition of dominant runoff generation mechanisms (percentages relative to mechanism-specific sample size). Percentages are calculated relative to the total number of catchments reporting each mechanism, such that each bar sums to 100%.

SSF- and SOF–SSF-dominated catchments are primarily found in humid climates, with smaller contributions from semi-humid and semi-arid regions. SOF-dominated catchments are distributed across humid and semi-humid climates, with some occurrences in semi-arid

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environments. HOF-dominated catchments are found across all aridity classes, with the largest proportion in semi-arid climates, followed by humid catchments. GWF-dominated catchments are restricted to humid and semi-humid climates, with no occurrences in semi-arid or arid regions.

3.4 Transitions of dominant runoff generation mechanisms under increasing wetness

We synthesized evidence from 23 experimental catchments where changes in dominant runoff generation mechanisms were explicitly reported during storm events or across event sequences under increasing catchment wetness. These catchments provide direct observations of mechanism transitions under evolving hydrological conditions.

Figure 6 illustrates the observed transition pathways among dominant runoff generation mechanisms. The most commonly reported initial dominant mechanisms are HOF (12 catchments) and SOF (9 catchments), while fewer catchments exhibit SSF or GWF as the initial mechanism. Node size reflects the total number of catchments with a given initial mechanism, and flow bands returning to the same node indicate instances where the dominant mechanism remains unchanged. These self-links, which may appear as circular loops in the Sankey diagram, represent cases where the mechanism did not change across the wetness gradient.

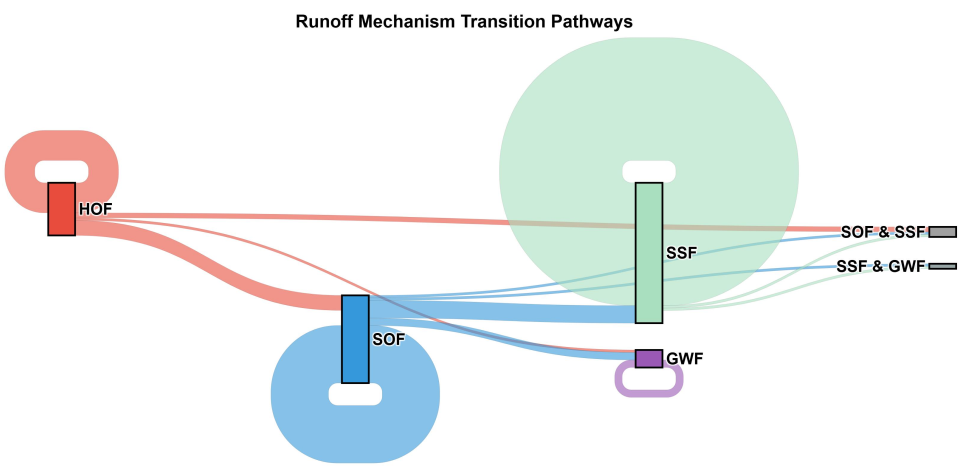

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Figure 6. Sankey diagram illustrating observed transition pathways of dominant runoff generation mechanisms ~~under~~ increasing wetness. Rectangular nodes represent runoff generation mechanisms, with node size reflecting the total number of catchments reporting each mechanism. Directed flow bands represent observed transitions between mechanisms as wetness increases, with band width proportional to the number of catchments exhibiting each transition. Flow bands returning to the same node indicate cases where the dominant mechanism remains unchanged.

~~As wetness increases, multiple transition pathways are observed.~~ For catchments initially dominated by HOF, transitions typically occur toward SOF, combined SOF–SSF responses, and less frequently, groundwater-dominated flow. Catchments initially dominated by SOF transition to SSF, GWF, and mixed SOF–SSF and SSF–GWF responses. Transitions originating from SSF are less frequent but include shifts toward ~~combined subsurface- and groundwater-dominated mechanisms.~~

~~The conditional structure of these transitions is presented in Fig. 7, which shows transition probabilities based on the number of catchments with a given initial dominant mechanism. For HOF-dominated catchments, transitions to SOF account for approximately 29%, followed by transitions to SOF–SSF (10%) and GWF (5%). For SOF-dominated catchments, the most frequent transition is toward SSF (20%), with additional transitions to GWF (9%), SOF–SSF (3%), and SSF–GWF (3%). For SSF-dominated catchments, transitions include shifts to~~ SOF–SSF (4%) and SSF–GWF (2%).

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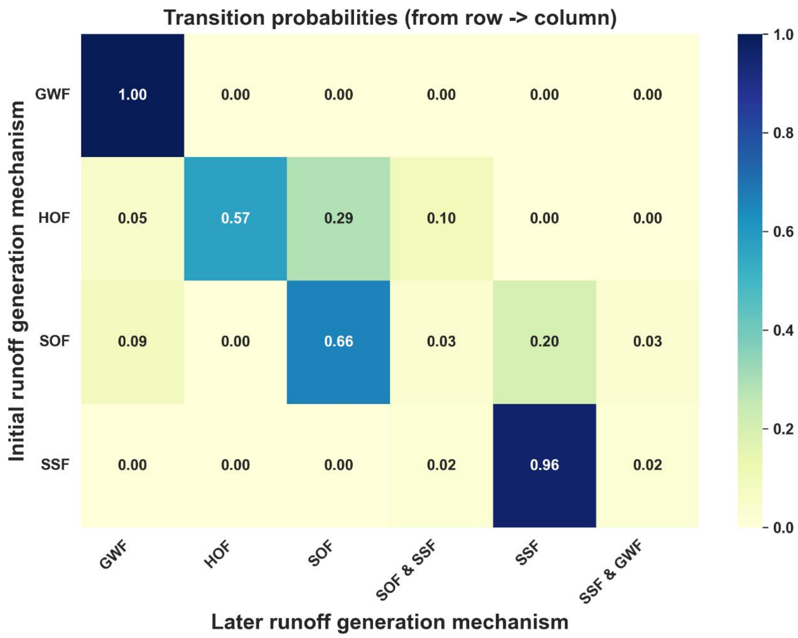

Figure 7. Conditional transition probabilities between dominant runoff generation mechanisms under increasing wetness. Values represent the proportion of catchments with a given initial mechanism (rows) that transitioned to each subsequent mechanism (columns).

Across the compiled catchments, transitions are predominantly from surface-dominated mechanisms to subsurface- and groundwater-dominated mechanisms. Reverse transitions, from subsurface or groundwater-dominated flow to surface-dominated runoff, are rarely reported. To evaluate whether the observed directional tendency differs from random reorganization, we compared the empirical transition matrix with a null model assuming equal transition probabilities. Surface-to-subsurface transitions occurred significantly more frequently than expected under the null hypothesis (permutation test, $p < 0.05$).

3.5 Soil–geology fingerprints of runoff generation mechanisms

To characterize the structural environments associated with different dominant runoff generation mechanisms, we conducted a soil–geology keyword co-occurrence analysis for 103 ~~representative~~ catchments~~, each~~ with a clearly identified dominant mechanism. ~~Descriptors related to soil texture, soil structural properties, lithology, and geological structure were systematically extracted from the literature and synthesized into four co-occurrence networks~~

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(Fig. 8a d). Link thickness represents the frequency of repeated co-occurrence across independent catchments, emphasizing recurrent soil geology associations rather than site-specific attributes.

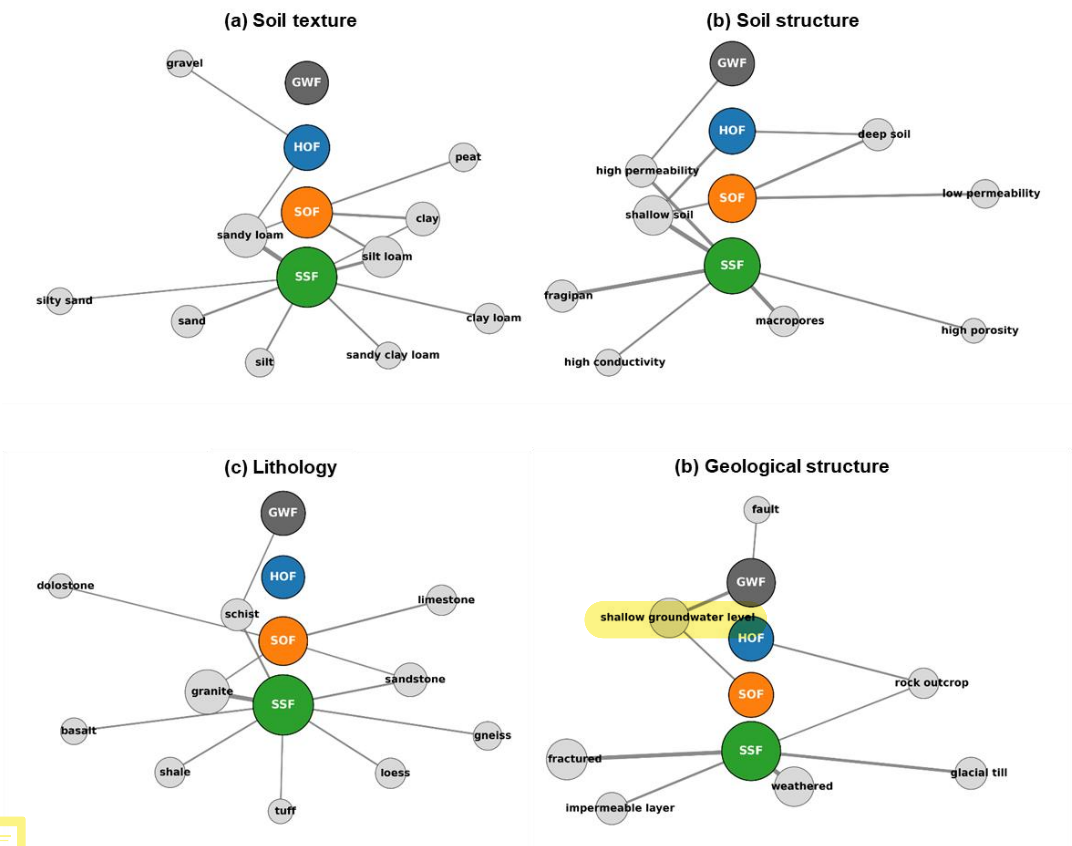

Figure 8. Soil–geology fingerprints of dominant runoff generation mechanisms. Panels show co-occurrence relationships with (a) soil texture, (b) soil structural properties, (c) lithology, and (d) geological structure. Colored nodes represent dominant runoff mechanisms—HOF, SOF, SSF, and GWF—while gray nodes represent soil or geological keywords extracted from the literature. Node size reflects the frequency of occurrence across reviewed catchments, and link thickness indicates the number of independent catchments in which a given mechanism and descriptor co-occur.

Catchments dominated by HOF are associated with a limited set of soil and geological descriptors. The most frequent associations include shallow soils, gravel, rock outcrops, and coarse surface materials. A smaller number of HOF-dominated catchments are found in areas with exceptionally deep soil profiles.

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~~SOF exhibits a more distinct and coherent pattern of soil and geological associations.~~ Strong co-occurrence links ~~connect~~ SOF ~~to~~ clay and loam textures, deep soils, and low permeability. It is also frequently associated with ~~dense lithologies, such as~~ granite, limestone, and dolostone, as well as with shallow groundwater conditions.

SSF has the most diverse co-occurrence structure of the four mechanisms. It is commonly associated with shallow soils, fragipans, macropores, and high permeability. Additional links connect SSF to silt loam and sandy loam textures, and to fractured or weathered bedrock types, including granite and shale.

GWF, while having a more compact but distinct co-occurrence pattern, is most strongly associated with shallow groundwater levels and structurally conductive geological settings, such as schist, faults, and fractured formations. In contrast, GWF shows weak and non-specific associations with soil textures, and soil structural properties ~~are infrequently reported in GWF-dominated catchments~~.

Overall, the four co-occurrence networks highlight recurring combinations of soil depth, texture, permeability, lithology, and geological structure associated with different dominant runoff generation mechanisms. These associations occupy distinct, though partially overlapping, regions of the soil–geology attribute space across the reviewed catchments.

4. Discussion

4.1 What do runoff thresholds represent across studies?

Across the reviewed literature, the term "runoff threshold" is consistently used to describe nonlinear stormflow responses, yet the synthesis in Section 3.1 reveals that these thresholds are not defined by a single, universal variable ~~or numeric value~~. Instead, threshold behavior is identified using a heterogeneous set of indicators, including rainfall-based metrics, hydrologic state variables, and composite indices combining forcing and antecedent conditions. This diversity reflects methodological differences and varying ~~conceptualizations of~~ runoff regime shifts across catchments and hydrologic settings.

A key finding is that rainfall alone ~~is insufficient~~ to explain nonlinear runoff responses. While precipitation acts as a trigger, abrupt runoff increases typically occur only when catchments approach critical internal states. Accordingly, rainfall-based thresholds often

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~~correlate~~ with antecedent wetness, soil moisture, or groundwater levels, suggesting that precipitation primarily triggers events rather than directly controlling regime shifts (Ali et al., 2015; Ross et al., 2021; Tromp-van Meerveld and McDonnell, 2006a, b).

In contrast, thresholds expressed in terms of soil moisture, catchment storage, or groundwater level better capture the state-dependence of nonlinear runoff behavior. These state variables ~~indicate the proximity to hydrologic connectivity activation, such as~~ saturation expansion, lateral subsurface flow initiation, and hillslope–channel coupling (Fu et al., 2013; McGuire and McDonnell, 2010; Penna et al., 2011). The prominence of state-based indicators across diverse climates and runoff mechanisms suggests that runoff thresholds are fundamentally state-controlled, though rainfall-triggered.

The use of composite indices highlights the inseparability of forcing and state effects in empirical studies. Rather than universally transferable threshold variables, these indices serve as practical proxies for the combined forcing-state conditions under which regime shifts occur. Their widespread use reflects the challenge of isolating internal states from external forcing in event-based studies, rather than evidence for a universal hydrologic threshold law.

~~These findings suggest that reported runoff thresholds should not be viewed as fixed, catchment-invariant constants.~~ Though thresholds are not directly comparable in terms of specific metrics or numeric values, they are conceptually comparable: across environments, thresholds ~~consistently signify~~ connectivity transitions, where incremental rainfall results in ~~disproportionate increases in internal~~ connectivity and runoff. Thus, cross-catchment comparability is found not in the threshold value, but in the connectivity transition it represents. This perspective reconciles the diversity of threshold indicators and provides a foundation for global synthesis, highlighting the need to examine how structural attributes influence state evolution and connectivity development.

Based on the global synthesis, two state indicators emerge as the most transferable across climatic and structural settings: (1) antecedent soil moisture or relative catchment storage, particularly effective in SOF- and SSF-dominated systems, and (2) groundwater level or water table depth, which captures hillslope–riparian connectivity in humid and groundwater-influenced catchments. These indicators ~~perform less consistently in~~ infiltration-excess-dominated systems, ~~where~~ rainfall intensity often overrides antecedent storage effects. While no universal numeric

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threshold exists, these state variables provide ~~the most~~ physically interpretable and cross-catchment comparable proxies of connectivity proximity.

4.2 Why do thresholds differ across mechanisms and catchments?

Differences in runoff threshold behavior across mechanisms and catchments primarily stem from how hydrologic connectivity develops within structurally constrained landscapes, rather than differences in rainfall forcing alone. Soil and geological structure define the subsurface architecture through which water is stored and transmitted, regulating both the rate of connectivity increase with wetness and the flow pathways activated (Blume and Van Meerveld, 2015; McGuire and McDonnell, 2010).

The soil–geology fingerprints identified in Section 3.5 show that dominant runoff mechanisms occupy distinct regions of structural attribute space. HOF-dominated catchments are typically characterized by shallow soils, coarse surface materials, and limited storage capacity (Kampf et al., 2018; Lana-Renault et al., 2013; Liu et al., 2022; Nanda and Sen, 2021), conditions that ~~favor rapid~~ infiltration ~~limitation~~ during high-intensity rainfall. SOF, on the other hand, emerges in settings with deeper, fine-textured soils and low-permeability substrates (Birkel et al., 2017; Camporese et al., 2014; Frei et al., 2010; Meyles et al., 2003; Penna et al., 2010; Steenhuis et al., 2013), ~~where vertical storage accumulation leads to~~ near-surface saturation and expansion of connected source areas. SSF and GWF are linked to more complex subsurface structures, such as permeability contrasts (Graham et al., 2010; Patankou et al., 2004; Wang et al., 2022a), preferential flow networks (Detty and McGuire, 2010; Haga et al., 2005; Lee and Kim, 2020; Zehe et al., 2007; Zillgens et al., 2007), fractured or weathered bedrock (Birch et al., 2021; Chappell et al., 2017; Cuomo and Guida, 2016; Nanda and Safeeq, 2023; Sahraei et al., 2020; Ye et al., 2023), and shallow groundwater tables (Cuomo and Guida, 2016; Gao et al., 2024; Graeff et al., 2009; Meyles et al., 2003; Scaife et al., 2020), all of which facilitate lateral and vertical connectivity at depth.

These structural differences explain ~~why similar rainfall amounts or antecedent wetness can produce~~ markedly different runoff responses across catchments. A given level of soil moisture or storage may trigger lateral subsurface pathways in one catchment, while remaining below the connectivity threshold in another. Structural attributes do not directly prescribe thresholds but regulate how rapidly hydrologic connectivity increases as system wetness evolves, and which

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pathways dominate once critical states are approached (McDonnell, 2013; McGuire and McDonnell, 2010; Saffarpour et al., 2016).

In this structurally constrained context, ~~the mechanism reorganizations observed in Section 3.4 exhibit a pronounced directional tendency under increasing wetness.~~ Responses most commonly evolve from HOF to SOF, and subsequently to SSF or GWF. This tendency corresponds to the sequential activation of connectivity pathways as storage elements fill—from surface runoff with limited storage, to saturation-driven overland flow, and ultimately to lateral and vertical subsurface transmission once internal hydraulic linkages are established (Blöschl, 2022; Cain et al., 2022; Lana-Renault et al., 2013; Saffarpour et al., 2016; Schnabel and Gómez-Gutiérrez, 2013). However, mechanisms frequently coexist, and dominance may shift gradually rather than abruptly, with alternative pathways emerging due to structural features like soil pipes or highly conductive bedrock.

~~By linking threshold behavior to structural constraints on connectivity evolution, this synthesis moves beyond merely documenting when specific runoff mechanisms occur. It clarifies how mechanism dominance reorganizes along wetness gradients, explaining why similar forcing leads to divergent nonlinear responses across landscapes.~~ Threshold differences across mechanisms and catchments arise not from fundamentally different rainfall controls but from how structural attributes translate state variables into connectivity gains and pathway activation, providing a unifying explanation for the diversity of threshold behavior in the literature.

~~It should be noted that humid catchments are overrepresented in the reviewed dataset, potentially biasing the apparent dominance of subsurface and groundwater transitions.~~ While directional reorganization remains evident within individual aridity classes, the limited number of arid and semi-arid systems constrains generalization toward strongly Hortonian environments.

4.3 A revised conceptual framework for storm runoff generation

Building on the global synthesis of thresholds, mechanism ~~distributions~~s, transition pathways, and soil–geology fingerprints, we propose a revised conceptual framework for storm runoff generation that integrates structure, state, and mechanism within a connectivity-based perspective (Fig. 9). In this framework, runoff thresholds are not fixed hydrologic constants, but emergent properties arising from dynamic interactions between rainfall forcing, evolving

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catchment states, and relatively stable structural constraints (Genxu et al., 2017; Graham et al., 2010; Ross et al., 2021; Wang et al., 2022b; Wilson et al., 2017; Zimmermann et al., 2014).

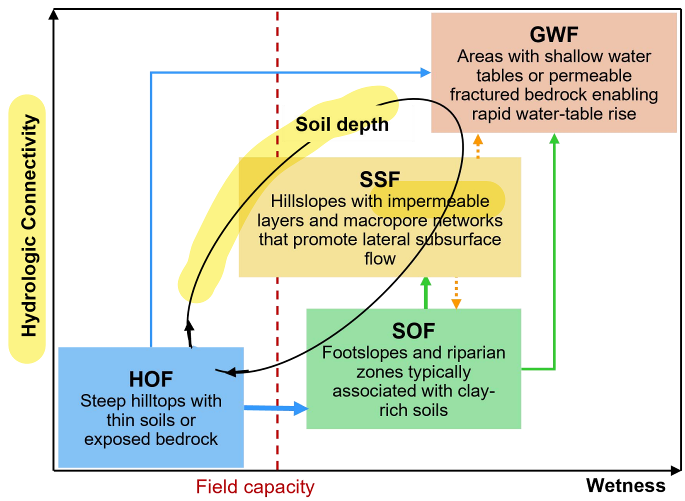

Figure 9. Conceptual framework of storm runoff generation across gradients of wetness and hydrologic connectivity. Solid arrows indicate commonly observed transition pathways between mechanisms as rainfall input and antecedent wetness increase, with arrow thickness representing the relative likelihood of transition. Dashed arrows denote less frequent but plausible transitions, highlighting alternative evolutionary pathways under specific structural or hydrologic conditions. The red dashed line marks the "field capacity" threshold, where soil retains ~~its maximum~~ water without significant drainage, marking the transition from soil moisture storage to runoff initiation.

Hydrologic connectivity serves as the central mediator linking structure, state, and runoff response. Catchment structure—defined by soil depth, texture, permeability contrasts, lithology, and geological architecture—constrains the pathways through which water can ~~be stored and~~ transmitted, thereby defining the space within which connectivity evolves (Ali and Roy, 2010; Blume and Van Meerveld, 2015; Wilson et al., 2017). While structural attributes evolve slowly relative to storm events, they exert primary control on runoff sensitivity to wetness changes.

State variables, including soil moisture, catchment storage, and groundwater level, describe the catchment's evolving position within this structurally constrained space. As wetness increases, storage elements fill and hydraulic linkages strengthen, activating new flow pathways. Nonlinear runoff responses arise when incremental rainfall produces disproportionate increases in connectivity, leading to the ~~reorganization of~~ flow pathways rather than gradual amplification of existing ones (Cui et al., 2024; Hrachowitz et al., 2013; Lehmann et al., 2007; Tromp-van

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Meerveld and McDonnell, 2006a, b; Zhang et al., 2021). In this context, thresholds mark connectivity transitions, with state variables serving as indicators of proximity to regime shifts rather than independent controls.

In this connectivity-based framework, runoff generation mechanisms are better understood as dynamic states rather than static, mutually exclusive categories. The transitions identified in this study—commonly from HOF to SOF, then to SSF or GWF—represent preferred but non-deterministic evolutionary pathways as wetness increases (Buttle et al., 2004; Cain et al., 2022; Haga et al., 2005; Latron and Gallart, 2008; Rogger et al., 2012). Structural heterogeneity, preferential flow networks, and subsurface drainage can modify or bypass these pathways, explaining why alternative transition sequences occur under similar forcing conditions.

Rainfall remains a necessary trigger for stormflow generation but does not solely determine runoff response. Identical rainfall events can induce negligible runoff or abrupt regime shifts depending on antecedent wetness and subsurface connectivity, reconciling the use of rainfall-based and composite threshold indicators with consistent evidence that internal state is key to explaining nonlinear behavior (Cain et al., 2022; Jin et al., 2020; Lee and Kim, 2020; McMillan and Srinivasan, 2015; Nanda and Safeeq, 2023; Redding and Devito, 2008; Williams et al., 2019). Thus, thresholds reflect occurrence conditions—specific combinations of triggering rainfall and internal state—rather than intrinsic properties of rainfall alone.

This revised framework advances our understanding of storm runoff generation in three key ways. First, it clarifies that cross-catchment comparability of runoff thresholds lies in connectivity transitions, not specific threshold values or variables. Second, it demonstrates that dominant runoff mechanisms undergo systematic but non-deterministic reorganization along wetness gradients, driven by structurally constrained connectivity evolution rather than rainfall forcing alone. Third, it provides a physically grounded synthesis that integrates event-scale threshold detection with established process-based runoff generation classifications. By conceptualizing nonlinear runoff responses as emergent connectivity within structurally constrained landscapes, the framework facilitates more coherent global comparisons, guides future observations to jointly resolve state dynamics and subsurface structure, and enhances the representation of threshold behavior in hydrological models.

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To extend this conceptual framework into hydrological modeling, we propose parameterizing connectivity transitions with state-dependent switching functions. These functions activate alternative flow pathways when soil storage or groundwater level exceeds critical fractions of maximum capacity, allowing models to simulate abrupt runoff amplification without fixed rainfall thresholds. This approach enables hydrological models to better represent the dynamic, state-dependent nature of runoff behavior, providing a more flexible and accurate depiction of threshold behavior.

5. Conclusions

This study synthesizes storm runoff threshold behavior across diverse experimental catchments by examining event-scale observations, threshold indicators, dominant runoff generation mechanisms, and soil–geological context. Our findings demonstrate that runoff thresholds are not fixed hydrologic constants, but emergent properties resulting from the interactions between rainfall forcing, evolving catchment states, and relatively stable structural constraints. Apparent inconsistencies among reported threshold variables do not reflect contradictory hydrologic behavior, but arise from differences in observational focus and the connectivity pathways that dominate runoff generation. Thus, meaningful cross-catchment comparison lies in identifying common connectivity transitions rather than comparing specific threshold metrics.

Across climates and landscapes, antecedent state variables consistently provide stronger explanatory power for nonlinear runoff responses than rainfall-based descriptors, indicating that threshold behavior is fundamentally state-controlled and rainfall-triggered. By synthesizing reported mechanism transitions, this study reveals a systematic reorganization of runoff generation with increasing wetness, where responses commonly shift from surface-dominated processes to subsurface- and groundwater-dominated pathways. These transitions reflect the progressive strengthening of hydrologic connectivity, driven by soil depth, permeability contrasts, subsurface architecture, and groundwater configuration, rather than rainfall forcing alone.

By disentangling triggering conditions, dynamic states, and structural controls and linking threshold indicators with shifts in dominant runoff mechanisms. This study establishes a unified, connectivity-based conceptual framework for storm runoff generation. Rather than pursuing

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~~universal threshold values, comparative hydrology should focus on recurrent rainfall state structure configurations that regulate connectivity and regime shifts. This approach provides a robust, physically grounded foundation for interpreting nonlinear runoff behavior across catchments and underscores the need for future observational and modeling efforts to jointly resolve subsurface structure, evolving connectivity, and state dynamics in understanding and representing runoff thresholds.~~

~~To enhance the representation of runoff thresholds in future studies, field observations should prioritize high-frequency measurements of soil moisture profiles, groundwater levels near hillslope-riparian interfaces, and indicators of subsurface connectivity. These observations should complement traditional rainfall metrics, providing a more comprehensive understanding of the dynamic processes driving runoff generation.~~

Data availability

The compiled catchment dataset used in this study will be archived in the Zenodo repository and made publicly available upon publication of the manuscript. The dataset link and DOI will be provided after acceptance.

Author contribution

ZC contributed the conceptualization, formal analysis, investigation and writing; FT contributed the conceptualization, formal analysis and revision.

Competing interests

Fuqiang Tian is a member of the editorial board of Hydrology and Earth System Sciences.

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References

Ali, G., Tetzlaff, D., McDonnell, J. J., Soulsby, C., Carey, S., Laudon, H., McGuire, K., Buttle, J., Seibert, J., and Shanley, J.: Comparison of threshold hydrologic response across northern catchments, Hydrological Processes, 29, 3575–3591, https://doi.org/10.1002/hyp.10527, 2015.

Ali, G. A. and Roy, A. G.: Shopping for hydrologically representative connectivity metrics in a humid temperate forested catchment, Water Resources Research, 46, 2010WR009442, https://doi.org/10.1029/2010WR009442, 2010.

Ares, M. G., Varni, M., and Chagas, C.: Runoff response of a small agricultural basin in the argentine Pampas considering connectivity aspects, Hydrological Processes, 34, 3102–3119, https://doi.org/10.1002/hyp.13782, 2020.

Birch, A. L., Stallard, R. F., and Barnard, H. R.: Precipitation Characteristics and Land Cover Control Wet Season Runoff Source and Rainfall Partitioning in Three Humid Tropical Catchments in Central Panama, Water Resources Research, 57, https://doi.org/10.1029/2020wr028058, 2021.

Birkel, C., Broder, T., and Biester, H.: Nonlinear and threshold-dominated runoff generation controls DOC export in a small peat catchment, JGR Biogeosciences, 122, 498–513, https://doi.org/10.1002/2016JG003621, 2017.

Blöschl, G.: Flood generation: process patterns from the raindrop to the ocean, Hydrol. Earth Syst. Sci., 26, 2469–2480, https://doi.org/10.5194/hess-26-2469-2022, 2022.

Blume, T. and Van Meerveld, H. J. (Ilja): From hillslope to stream: methods to investigate subsurface connectivity, WIREs Water, 2, 177–198, https://doi.org/10.1002/wat2.1071, 2015.

Buttle, J. M., Dillon, P. J., and Eerkes, G. R.: Hydrologic coupling of slopes, riparian zones and streams: an example from the Canadian Shield, Journal of Hydrology, 287, 161–177, https://doi.org/10.1016/j.jhydrol.2003.09.022, 2004.

Cain, M. R., Woo, D. K., Kumar, P., Keefer, L., and Ward, A. S.: Antecedent Conditions Control Thresholds of Tile-Runoff Generation and Nitrogen Export in Intensively Managed Landscapes, Water Resources Research, 58, e2021WR030507, https://doi.org/10.1029/2021WR030507, 2022.

Camporese, M., Penna, D., Borga, M., and Paniconi, C.: A field and modeling study of nonlinear storage-discharge dynamics for an Alpine headwater catchment: NONLINEAR STORAGE-DISCHARGE DYNAMICS OF AN ALPINE CATCHMENT, Water Resour. Res., 50, 806–822, https://doi.org/10.1002/2013WR013604, 2014.

Chappell, N. A., Jones, T. D., Tych, W., and Krishnaswamy, J.: Role of rainstorm intensity underestimated by data-derived flood model s: Emerging global evidence from subsurface-dominated watersheds, Environmental Modelling & Software, 88, 1–9, https://doi.org/10.1016/j.envsoft.2016.10.009, 2017.

Cui, Z., Tian, F., Zhao, Z., Xu, Z., Duan, Y., Wen, J., and Khan, M. Y. A.: Bimodal hydrographs in a semi-humid forested watershed: characteristics and occurrence conditions, Hydrol. Earth Syst. Sci., 28, 3613–3632, https://doi.org/10.5194/hess-28-3613-2024, 2024.

Cuomo, A. and Guida, D.: Using hydro-chemograph analyses to reveal runoff generation processes in a Mediterranean catchment, Hydrol. Process., 30, 4462–4476, https://doi.org/10.1002/hyp.10935, 2016.

Deng, C., Jiang, X., Tan, Z., and Nie, T.: Spatiotemporal variation of hydrological connectivity and its threshold effects on flood dynamics: An examination in the arid and semi-arid regions, China, Science of The Total Environment, 935, 173406, https://doi.org/10.1016/j.scitotenv.2024.173406, 2024.
Detty, J. M. and McGuire, K. J.: Threshold changes in storm runoff generation at a till-mantled headwater catchment, Water Resources Research, 46, 2009WR008102, https://doi.org/10.1029/2009WR008102, 2010.
Douinot, A., Iffly, J. F., Tailliez, C., Meisch, C., and Pfister, L.: Flood patterns in a catchment with mixed bedrock geology and a hilly l andscape: identification of flashy runoff contributions during storm e vents, Hydrol. Earth Syst. Sci., 26, 5185–5206, https://doi.org/10.5194/hess-26-5185-2022, 2022.
Frei, S., Lischeid, G., and Fleckenstein, J. H.: Effects of micro-topography on surface–subsurface exchange and runoff generation in a virtual riparian wetland — A modeling study, Advances in Water Resources, 33, 1388–1401, https://doi.org/10.1016/j.advwatres.2010.07.006, 2010.
von Freyberg, J., Radny, D., Gall, H. E., and Schirmer, M.: Implications of hydrologic connectivity between hillslopes and riparia n zones on streamflow composition, Journal of Contaminant Hydrology, 169, 62–74, https://doi.org/10.1016/j.jconhyd.2014.07.005, 2014.
Fu, C., Chen, J., Jiang, H., and Dong, L.: Threshold behavior in a fissured granitic catchment in southern China: 1. Analysis of field monitoring results, Water Resources Research, 49, 2519–2535, https://doi.org/10.1002/wrcr.20191, 2013.
Gao, H., Ju, Q., Zhang, D., Wang, Z., Hao, Z., and Kirchner, J. W.: Quantifying Dynamic Linkages Between Precipitation, Groundwater Recharge, and Runoff using Ensemble Rainfall-Runoff Analysis, https://doi.org/10.22541/essoar.171535928.81911940/v1, 10 May 2024.
Genxu, W., Tianxu, M., Juan, C., Chunlin, S., and Kewei, H.: Processes of runoff generation operating during the spring and autumn seasons in a permafrost catchment on semi-arid plateaus, Journal of Hydrology, 550, 307–317, https://doi.org/10.1016/j.jhydrol.2017.05.020, 2017.
Graeff, T., Zehe, E., Reusser, D., Lück, E., Schröder, B., Wenk, G., John, H., and Bronstert, A.: Process identification through rejection of model structures in a mid-mountainous rural catchment: observations of rainfall-runoff response, geophysical conditions and model inter-comparison, Hydrol. Process., 23, 702–718, https://doi.org/10.1002/hyp.7171, 2009.
Graham, C. B., Woods, R. A., and McDonnell, J. J.: Hillslope threshold response to rainfall: (1) A field based forensic approach, Journal of Hydrology, 393, 65–76, https://doi.org/10.1016/j.jhydrol.2009.12.015, 2010.
Green, D. I. S. and Crumpton, W. G.: Depressional runoff cascade networks of the Des Moines Lobe of Iowa, JAWRA Journal of the American Water Resources Association, 59, 824–854, https://doi.org/10.1111/1752-1688.13103, 2023.
Haga, H., Matsumoto, Y., Matsutani, J., Fujita, M., Nishida, K., and Sakamoto, Y.: Flow paths, rainfall properties, and antecedent soil moisture controlling lags to peak discharge in a granitic unchanneled catchment, Water Resources Research, 41, 2005WR004236, https://doi.org/10.1029/2005WR004236, 2005.
Hrachowitz, M., Savenije, H. H. G., Blöschl, G., McDonnell, J. J., Sivapalan, M., Pomeroy, J. W., Arheimer, B., Blume, T., Clark, M. P., Ehret, U., Fenicia, F., Freer, J. E., Gelfan, A.,

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Gupta, H. V., Hughes, D. A., Hut, R. W., Montanari, A., Pande, S., Tetzlaff, D., Troch, P. A., Uhlenbrook, S., Wagener, T., Winsemius, H. C., Woods, R. A., Zehe, E., and Cudennec, C.: A decade of Predictions in Ungauged Basins (PUB)—a review, Hydrological Sciences Journal, 58, 1198–1255, https://doi.org/10.1080/02626667.2013.803183, 2013.

James, A. L. and Roulet, N. T.: Investigating hydrologic connectivity and its association with threshold change in runoff response in a temperate forested watershed, Hydrological Processes, 21, 3391–3408, https://doi.org/10.1002/hyp.6554, 2007.

Jehn, F. U., Breuer, L., Kraft, P., Bestian, K., and Houska, T.: Simple Catchments and Where to Find Them: The Storage-Discharge Relationship as a Proxy for Catchment Complexity, Frontiers in Water, 3, https://doi.org/10.3389/frwa.2021.631651, 2021.

Jin, Z., Guo, L., Yu, Y., Luo, D., Fan, B., and Chu, G.: Storm runoff generation in headwater catchments on the Chinese Loess Plateau after long-term vegetation rehabilitation, Science of The Total Environment, 748, 141375, https://doi.org/10.1016/j.scitotenv.2020.141375, 2020.

Kampf, S. K., Faulconer, J., Shaw, J. R., Lefsky, M., Wagenbrenner, J. W., and Cooper, D. J.: Rainfall Thresholds for Flow Generation in Desert Ephemeral Streams, Water Resources Research, 54, 9935–9950, https://doi.org/10.1029/2018WR023714, 2018.

Kirchner, J. W.: Characterizing nonlinear, nonstationary, and heterogeneous hydrologic behavior using ensemble rainfall–runoff analysis (ERRA): proof of conc ept, Hydrol. Earth Syst. Sci., 28, 4427–4454, https://doi.org/10.5194/hess-28-4427-2024, 2024.

Lana-Renault, N., Nadal-Romero, E., Serrano-Muela, M. P., Alvera, B., Sánchez-Navarrete, P., Sanjuan, Y., and García-Ruiz, J. M.: Comparative analysis of the response of various land covers to an exce ptional rainfall event in the central Spanish Pyrenees, October 2012, Earth Surf Processes Landf, 39, 581–592, https://doi.org/10.1002/esp.3465, 2013.

Latron, J. and Gallart, F.: Runoff generation processes in a small Mediterranean research catchment (Vallcebre, Eastern Pyrenees), Journal of Hydrology, 358, 206–220, https://doi.org/10.1016/j.jhydrol.2008.06.014, 2008.

Lee, E. and Kim, S.: Characterization of runoff generation in a mountainous hillslope according to multiple threshold behavior and hysteretic loop features, Journal of Hydrology, 590, 125534, https://doi.org/10.1016/j.jhydrol.2020.125534, 2020.

Lehmann, P., Hinz, C., McGrath, G., Meerveld, H. J. T., and McDonnell, J. J.: Rainfall threshold for hillslope outflow: an emergent property of flow pathway connectivity, Hydrol. Earth Syst. Sci., 2007.

Liu, T., McGuire, L. A., Oakley, N., and Cannon, F.: Temporal changes in rainfall intensity–duration thresholds for post-wildfire flash floods in southern California, Nat. Hazards Earth Syst. Sci., 22, 361–376, https://doi.org/10.5194/nhess-22-361-2022, 2022.

Martínez-Carreras, N., Hissler, C., Gourdol, L., Klaus, J., Juilleret, J., Iffly, J. F., and Pfister, L.: Storage controls on the generation of double peak hydrographs in a forested headwater catchment, Journal of Hydrology, 543, 255–269, https://doi.org/10.1016/j.jhydrol.2016.10.004, 2016.

McDonnell, J. J.: Are all runoff processes the same?, Hydrological Processes, 27, 4103–4111, https://doi.org/10.1002/hyp.10076, 2013.

McGuire, K. J. and McDonnell, J. J.: Hydrological connectivity of hillslopes and streams: Characteristic time scales and nonlinearities, Water Resources Research, 46, 2010WR009341, https://doi.org/10.1029/2010WR009341, 2010.

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McMillan, H., Araki, R., Bolotin, L., Kim, D.-H., Coxon, G., Clark, M., and Seibert, J.: Global patterns in observed hydrologic processes, Nat Water, 3, 497–506, https://doi.org/10.1038/s44221-025-00407-w, 2025.

McMillan, H. K. and Srinivasan, M. S.: Characteristics and controls of variability in soil moisture and groundwater in a headwater catchment, Hydrol. Earth Syst. Sci., 19, 1767–1786, https://doi.org/10.5194/hess-19-1767-2015, 2015.

Mentzafou, A., Papadopoulos, A., and Dimitriou, E.: Flood generating mechanisms investigation and rainfall threshold identification for regional flood early warning, Environ Earth Sci, 82, 242, https://doi.org/10.1007/s12665-023-10938-8, 2023.

Meyles, E., Williams, A., Ternan, L., and Dowd, J.: Runoff generation in relation to soil moisture patterns in a small Dartmoor catchment, Southwest England, Hydrological Processes, 17, 251–264, https://doi.org/10.1002/hyp.1122, 2003.

Mirus, B. B. and Loague, K.: How runoff begins (and ends): Characterizing hydrologic response at th e catchment scale, Water Resources Research, 49, 2987–3006, https://doi.org/10.1002/wrcr.20218, 2013.

Nanda, A. and Safeeq, M.: Threshold controlling runoff generation mechanisms in Mediterranean headwater catchments, Journal of Hydrology, 620, 129532, https://doi.org/10.1016/j.jhydrol.2023.129532, 2023.

Nanda, A. and Sen, S.: A complex network theory based approach to better understand the infiltration-excess runoff generation thresholds, Journal of Hydrology, 603, 127038, https://doi.org/10.1016/j.jhydrol.2021.127038, 2021.

Patankou, P., Tesarm, M., and Ák, Í. J. P. ˇ: Instability driven flow and runoff formation in a small catchment, https://doi.org/10.1344/105.000001435, 2004.

Penna, D., van-Meerveld, H. J. T., Gobbi, A., and Borga, M.: Non-linearity of runoff generation processes in an alpine headwater catchment, 2010.

Penna, D., Tromp-van Meerveld, H. J., Gobbi, A., Borga, M., and Dalla Fontana, G.: The influence of soil moisture on threshold runoff generation processes in an alpine headwater catchment, Hydrol. Earth Syst. Sci., 15, 689–702, https://doi.org/10.5194/hess-15-689-2011, 2011.

Redding, T. E. and Devito, K. J.: Lateral flow thresholds for aspen forested hillslopes on the Western Boreal Plain, Alberta, Canada, Hydrological Processes, 22, 4287–4300, https://doi.org/10.1002/hyp.7038, 2008.

Rogger, M., Pirkl, H., Viglione, A., Komma, J., Kohl, B., Kirnbauer, R., Merz, R., and Blöschl, G.: Step changes in the flood frequency curve: Process controls, Water Resources Research, 48, https://doi.org/10.1029/2011wr011187, 2012.

Ross, C. A., Ali, G. A., Spence, C., and Courchesne, F.: Evaluating the Ubiquity of Thresholds in Rainfall-Runoff Response Across Contrasting Environments, Water Resources Research, 57, e2020WR027498, https://doi.org/10.1029/2020WR027498, 2021.

Ruggenthaler, R., Schöberl, F., Markart, G., Klebinder, K., Hammerle, A., and Leitinger, G.: Quantification of Soil Moisture Effects on Runoff Formation at the Hillslope Scale, J. Irrig. Drain Eng., 141, 05015001, https://doi.org/10.1061/(ASCE)IR.1943-4774.0000880, 2015.

Saffarpour, S., Western, A. W., Adams, R., and McDonnell, J. J.: Multiple runoff processes and multiple thresholds control agricultural runoff generation, Hydrol. Earth Syst. Sci., 20, 4525–4545, https://doi.org/10.5194/hess-20-4525-2016, 2016.

Sahraei, A., Kraft, P., Windhorst, D., and Breuer, L.: High-Resolution, In Situ Monitoring of Stable Isotopes of Water Revealed Insight into Hydrological Response Behavior, Water, 12, 565, https://doi.org/10.3390/w12020565, 2020.
Scaife, C. I., Singh, N. K., Emanuel, R. E., Miniat, C. F., and Band, L. E.: Non-linear quickflow response as indicators of runoff generation mechanisms, Hydrological Processes, 34, 2949–2964, https://doi.org/10.1002/hyp.13780, 2020.
Schnabel, S. and Gómez-Gutiérrez, A.: The role of interannual rainfall variability on runoff generation in a small dry sub-humid watershed with disperse tree cover, CIG, 39, 259–285, https://doi.org/10.18172/cig.1991, 2013.
Sidle, R. C., Tsuboyama, Y., Noguchi, S., Hosoda, I., Fujieda, M., and Shimizu, T.: Stormflow generation in steep forested headwaters: a linked hydrogeomorphic paradigm, Hydrol. Process., 14, 369–385, https://doi.org/10.1002/(SICI)1099-1085(20000228)14:3%253C369::AID-HYP943%253E3.0.CO;2-P, 2000.
Steenhuis, T. S., Hrnčíř, M., Poteau, D., Romero Luna, E. J., Tilahun, S. A., Caballero, L. A., Guzman, C. D., Stoof, C. R., Šanda, M., Yitaferu, B., and Císlerová, M.: A Saturated Excess Runoff Pedotransfer Function for Vegetated Watershe ds, Vadose Zone Journal, 12, 1–10, https://doi.org/10.2136/vzj2013.03.0060, 2013.
Tromp-van Meerveld, H. J. and McDonnell, J. J.: Threshold relations in subsurface stormflow: 1. A 147-storm analysis of the Panola hillslope, Water Resources Research, 42, 2004WR003778, https://doi.org/10.1029/2004WR003778, 2006a.
Tromp-van Meerveld, H. J. and McDonnell, J. J.: Threshold relations in subsurface stormflow: 2. The fill and spill hypothesis, Water Resources Research, 42, 2004WR003800, https://doi.org/10.1029/2004WR003800, 2006b.
Wang, S., Yan, Y., Fu, Z., and Chen, H.: Rainfall-runoff characteristics and their threshold behaviors on a karst hillslope in a peak-cluster depression region, Journal of Hydrology, 605, 127370, https://doi.org/10.1016/j.jhydrol.2021.127370, 2022a.
Wang, Y., Gao, L., Huang, S., and Peng, X.: Combined effects of rainfall types and antecedent soil moisture on runoff generation at a hillslope of red soil region, European J Soil Science, 73, e13274, https://doi.org/10.1111/ejss.13274, 2022b.
Williams, M. R., Livingston, S. J., Heathman, G. C., and McAfee, S. J.: Thresholds for run-off generation in a drained closed depression, Hydrological Processes, 33, 2408–2421, https://doi.org/10.1002/hyp.13477, 2019.
Wilson, G. V., Nieber, J. L., Fox, G. A., Dabney, S. M., Ursic, M., and Rigby, J. R.: Hydrologic connectivity and threshold behavior of hillslopes with fragipans and soil pipe networks, Hydrological Processes, 31, 2477–2496, https://doi.org/10.1002/hyp.11212, 2017.
Ye, S., Liu, L., Li, J., Pan, H., Li, W., and Ran, Q.: From rainfall to runoff: The role of soil moisture in a mountainous catchment, Journal of Hydrology, 625, 130060, https://doi.org/10.1016/j.jhydrol.2023.130060, 2023.
Zehe, E., Elsenbeer, H., Lindenmaier, F., Schulz, K., and Blöschl, G.: Patterns of predictability in hydrological threshold systems, Water Resources Research, 43, https://doi.org/10.1029/2006wr005589, 2007.
Zhang, G., Cui, P., Gualtieri, C., Zhang, J., Ahmed Bazai, N., Zhang, Z., Wang, J., Tang, J., Chen, R., and Lei, M.: Stormflow generation in a humid forest watershed controlled by antecedent wetness and rainfall amounts, Journal of Hydrology, 603, 127107, https://doi.org/10.1016/j.jhydrol.2021.127107, 2021.

https://doi.org/10.5194/egusphere-2026-1265
Preprint. Discussion started: 12 March 2026
© Author(s) 2026. CC BY 4.0 License.

Zillgens, B., Merz, B., Kirnbauer, R., and Tilch, N.: Analysis of the runoff response of an alpine catchment at different scales, Hydrol. Earth Syst. Sci., 2007.

Zimmermann, B., Zimmermann, A., Turner, B. L., Francke, T., and Elsenbeer, H.: Connectivity of overland flow by drainage network expansion in a rain forest catchment: CONNECTIVITY OF OVERLAND FLOW IN A RAINFOREST CATCHMENT, Water Resour. Res., 50, 1457–1473, https://doi.org/10.1002/2012WR012660, 2014.

https://doi.org/10.5194/egusphere-2026-1265
Preprint. Discussion started: 12 March 2026
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851 **Appendix A.**

852 **Table A1.** Simplified summary of watershed attributes and runoff generation mechanisms.

Watershed	Country	Threshold variable	State variable	Dominant runoff generation mechanism
ARW	India	Pi	AMC	HOF
Izas	Spain	-	-	HOF
LCC	Italy	-	AMC	SOF
Andit Tid	Ethiopia	P	AMC	SOF
Anjeni	Ethiopia	P	AMC	SOF
La Tigra	Honduras	P	AMC	SOF & SSF
Lake Enriquillo	Dominican Republic	P	AMC	SOF
Lake Saumatre	Haiti	P	AMC	SOF
Maybar	Ethiopia	P	AMC	SOF
Uhlířská	Czech Republic	P	AMC	SOF & SSF
LMW	USA	SWC	SWC & GWL	SOF
Saalach	Austria	-	AMC	SSF
USR	USA	ASI & P	SWC & GWL	SSF & GWF
XEW	China	ASI & P	SWC & GWL	GWF
Plynlimon	United Kingdom	-	Storage	SOF
LGC	New Zealand	ASI & P	ASW	SOF
Bongsunsa	Korea	ASI & P	ASW	SSF
MSRB	Japan	API	AMC	SSF
RRC	USA	-	AMC	SSF
FSSF	Brazil	-	ASW	SOF & SSF
Yingtan	China	ASI & P	ASW	SOF
Araguás	Spain	-	-	HOF
Arnás	Spain	-	AMC	SOF & SSF
SSC	Spain	-	AMC	SSF & GWF
Girnock	UK	P	AMC	SOF & SSF
HJA	USA	P	AMC	SOF & SSF

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Hubbard Brook	USA	P	AMC	SOF & SSF
Krycklan	Sweden	P	AMC	SOF & SSF
Mharcaidh	UK	P	-	SOF & SSF
Sleepers River	USA	P	AMC	SOF & SSF
BBC	United Kingdom	-	Storage	SOF
Lutzito	Panama	Storage	AMC	SOF
SNWR	USA	-	AMC	SOF & SSF
LEC	Germany	Storage	Storage	SOF
CCW	Canada	P	AMC	SOF
HRM	Canada	P	AMC	SOF & SSF
MRC	New Zealand	P	AMC	SOF & SSF
Baratz	Italy	SWC & GWL	SWC & GWL	SOF & SSF
Pinios	Greece	P	-	SOF
HM	Luxembourg	-	-	SOF & SSF
KOE	Luxembourg	-	AMC	SOF & GWF
L1	Japan	ASI & P	ASW	SSF
JPG	China	ASI & P	ASW	SSF
SEO	Germany	-	-	SSF
SIR	Chile	P	SWC	SOF
Maimai	New Zealand	P	-	SSF
Toro	USA	-	-	HOF & SOF
Utuado	USA	-	ASW	SSF
Uhlirska	Czech Republic	-	AMC	SSF
GCC	France	SWC	ASW	SSF
C3	USA	-	-	SSF
CB	USA	-	-	SSF
R5	USA	-	-	HOF & SOF
TW	Australia	-	AMC	SOF
GCEW	USA	ASI & P	ASW	SSF
PC1-08	Canada	GWL	GWL	SOF & SSF
Marcell	USA	-	ASW	SOF & SSF

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WS10	USA	P	AMC	SSF
PLB	Canada	-	AMC	SSF
PEC	United Kingdom	-	ASW	SOF & SSF
URHB	Switzerland	P	AMC	SOF & SSF
Liz	Czech Republic	SWC	SWC	SSF
PSC	USA	P	-	SSF
Westcreek	Canada	SWC	SWC	SSF
URSA	Canada	ASI & P	ASW	SSF
Ponderosa	USA	SWC	ASW	SSF
Hermine	Canada	Storage	Storage	SSF
RBF	Australia	ASI & P	ASW	SOF & SSF
Odersprung	Germany	GWL	GWL	SOF
CHL	USA	ASI & P	ASW	SSF
SHW	USA	ASI & P	SWC	GWF
HOAL	Austria	SWC	SWC	SOF
BEC	Australia	-	GWL	SSF
Tannhausen	Germany	SWC	SWC	SOF
Weiherbach	Germany	SWC	ASW	SSF
RCRW	Canada	GWL	AMC	SSF
Woldong	Korea	API	AMC	SSF
ASW	Panama	-	-	SSF
WWC	Australia	SWC	SWC	SOF & SSF
Schäfertal	Germany	-	AMC	GWF
Fenghuoshan	China	SWC	SWC	SOF & SSF
Inzing	Austria	SWC	ASW	SOF
Mösern	Austria	SWC	ASW	SOF
Yanglou	China	P	AMC	GWF
MWYW	USA	Pi	-	HOF
WGEW	USA	Pi	-	HOF
Mulian	China	ASI & P	ASW	SSF
Corbeira	Spain	P	AMC	SSF

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HRW	Canada	-	-	SOF & SSF
Baru	Malaysia	-	-	SSF
Greenholes	United Kingdom	-	-	SSF
Hafre	United Kingdom	-	-	SSF
NCB	United Kingdom	-	-	SSF
Saimane	India	-	-	SSF
SCB	Australia	-	-	SSF
UEC	Czech Republic	P	ASW	SSF
Alptal	Switzerland	-	GWL	SOF
HMD	UK	SWC	ASW	SSF
Ina	Japan	P	AMC	SSF & GWF
MNC	Japan	ASI & P	ASW	SSF
CVC	Spain	SWC	SWC	SOF
AEB	Brazil	P	-	HOF
VSC	Argentina	P	AMC	SSF
Jiufeng	China	SWC	ASW	HOF
Matalom	Philippines	P	ASW	SOF & SSF
Ressi	Italy	ASI & P	ASW	SSF
DFP	USA	SWC	ASW	SOF
LZW	Mexico	SWC	ASW	SSF
CRC	Spain	P	AMC	SOF
Mahurangi	New Zealand	P	ASW	SOF & SSF
BCC	Italy	ASI & P	ASW	SSF & GWF
WAWC	Austria	P	Storage	SOF & SSF
Weierbach	Luxembourg	Storage	Storage	GWF
Nanxiaohe	China	ASI & P	ASW	HOF
LXR	China	ASI & P	ASW	SSF
HOEW	Japan	API	AMC	SSF
SDSC	China	ASI & P	ASW	SSF
GRC	USA	Storage	Storage	SSF
SH	USA	SWC	Storage	SOF & SSF

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TSF	New Zealand	-	AMC	SSF
UASW	USA	Pi	-	HOF
HEB	Japan	P	-	GWF
MEW	Côte d'Ivoire	-	SWC	SSF
RDN	Spain	P	-	HOF
RVB	Italy	SWC	ASW	SSF
PEW	Spain	SWC	ASW	SOF & SSF
CERB	China	P	ASW	SSF
WS3	USA	ASI & P	SWC	SSF
KREW	USA	ASI & P	ASW	SSF
PMRW	USA	P	ASW	SSF
DCD	USA	ASI & P	AMC	SSF
UGCC	Canada	GWL	SWC	SSF
Quinuas	Ecuador	SWC	-	SSF
Ciciriello	Italy	-	ASW	GWF
OCR	USA	SWC	-	SSF
UP1	Canada	Storage	Storage	SOF
HBEF	USA	-	ASW	SOF & SSF

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Table A2. Synonym normalization of soil–geology descriptors used in the literature synthesis.

Original terms reported in literature	Standardized descriptor used in this study
shallow regolith, thin soils, shallow soils, shallow earth	shallow soil
deep permeable soil, thick soil profile, thick organic matter layer, deep loess	deep soil
high hydraulic conductivity, high infiltration capacity	high conductivity
low hydraulic conductivity	low conductivity
shallow impermeable horizon	impermeable layer
fractured bedrock, fractured rock, tectonic fracture, structural fracture, high fractures	fractured bedrock
bedrock exposure, bare bedrock, exposed bedrock, rocky outcrops	rock outcrop
shallow water table, shallow groundwater level, shallow water table depth	shallow groundwater level
macropores, macroporous	macropores
low permeability substrate, low-permeability layer, low permeability soils	low permeability
high permeability, highly permeable soils	high permeability