Runoff thresholds mechanism transitions, ~~as~~ and state-dependent connectivity ~~transitions~~: A global synthesis across diverse catchments

Zhen Cui, Fuqiang Tian*

[1] State Key Laboratory of Hydroscience and Engineering & Department of Hydraulic Engineering, Tsinghua University, Beijing 100084, China.

Corresponding to: Fuqiang Tian (tianfq@tsinghua.edu.cn)

Key Points:

- Reported runoff thresholds are more often characterized by antecedent or within-event catchment-state indicators than by rainfall metrics alone~~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 – hydrogeology associations provide structural context for interpreting ~~combinations create transferable structural fingerprints that govern~~ threshold behavior, and connectivity development. ~~and mechanism transitions.~~

Abstract

Runoff threshold behavior is widely reported in event-based hydrological studies, but its interpretation and cross-catchment comparability remain unresolved because threshold metrics, values, and process interpretations vary among climates and landscape settingsdue to variations in threshold metrics and values across climates, landscape structures, and observational focuses. synthesizes reported storm-runoff thresholds from 138 experimental catchments worldwide by compiling threshold indicators, reported dominant runoff mechanisms, documented wetness-dependent mechanism transitions, and recurring soil-geology-hydrogeology associations. Across the reviewed literature, threshold-like responses were identified using diverse rainfall-based, state-based, and composite indicators, with antecedent and within-event state descriptors reported more frequently than rainfall-only metrics. Subsurface- and saturation-related mechanisms were most frequently reported, particularly among humid catchments. In studies that explicitly documented event-scale mechanism transitions, the dominant mechanism tended to shift from surface-dominated responses toward saturation-, subsurface-, or shallow-groundwater-influenced pathways as catchment wetness increased, although these pathways were non-universal and structurally conditioned. Co-occurrence analysis indicates that reported mechanisms are associated with recurring soil-depth, texture, permeability, lithology, and hydrogeological descriptors, which we interpret as structural contexts that condition state-dependent functional connectivity. Together, the synthesis supports a connectivity-based framework in which rainfall forcing interacts with catchment state and structural constraints to activate or reorganize runoff pathways, while recognizing that connectivity is a conceptual framework rather than a directly measured universal index.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

1. Introduction

Storm runoff generation often exhibits ~~strong~~ nonlinearity or~~and~~ threshold-like behavior, where small changes in rainfall or antecedent wetness can trigger disproportionate increases in runoff. Numerous event-based studies ~~have shown~~show that runoff outcomes vary with~~similar storms may generate vastly different runoff outcomes depending on~~ catchment wetness, storage conditions, and activation of surface, subsurface, or groundwater pathways~~subsurface flow activation~~ (Blume and Van Meerveld, 2015; Penna et al., 2011; Sidle et al., 2000; Tromp-van Meerveld and McDonnell, 2006a). Such responses have often been interpreted as the activation of previously inactive flow paths or hydrologic connectivity under sufficiently wet catchment states, emphasizing the joint roles of rainfall forcing, antecedent wetness, storage, and flow-path organization. ~~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.~~

Connectivity- and storage-based frameworks have therefore~~Subsequent advances~~ shifted attention~~focus~~ from fixed rainfall thresholds to state-dependent activation of flow paths~~hydrologic connectivity~~. Fill-and-spill concepts emphasize~~d~~ the episodic filling and coupling of surface, subsurface, or depressional storage~~activation and coupling of subsurface and depressional storage once critical wetness thresholds are exceeded~~ (McDonnell et al., 2021; Spence and Woo, 2003; Tromp-van Meerveld and McDonnell, 2006b), while hydrologic connectivity theory ~~framed~~ frames runoff response as an ~~emergent~~ outcome of progressively coupled hillslopes, soils, groundwater, and channels (Blume and Van 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 this conceptual progress, cross-catchment synthesis remains limited. Threshold-like responses have been documented for infiltration-excess overland flow, saturation-excess overland flow, subsurface stormflow, and shallow groundwater-dominated responses~~ 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; Ross et al., 2021; Sidle et al., 2000; Scaife et al., 2020~~Lana-Renault et al., 2013; Ross et al., 2021~~)~~)~~, but threshold indicators, mechanism interpretations, and structural controls are often examined separately. A synthesis linking threshold reporting to runoff mechanisms and catchment structure is therefore needed~~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, connectivity structures, and dominant pathways lead to contrasting runoff responses under similar storm conditions remains lacking~~.

Several studies provide important foundations. ~~(~~Ross et al.~~,~~ (2021) tested threshold behavior across contrasting environments and proposed a typology of threshold dynamics; Ali et al. (2015) compared threshold hydrologic responses across northern catchments; and McDonnell et al. (2021)

developed fill-and-spill as a cross-scale framework for storage activation and connectivity. Broader syntheses by (McMillan et al., (2025), (McMillan et al., (2022), and (Penna, (2026) have further organized global runoff-process knowledge, process terminology, and controls on runoff processes in forested catchments.

These studies leave a specific gap for the present review. Threshold-focused comparisons have emphasized detection, typology, or specific climatic settings, whereas process syntheses have focused on dominant pathways, controls, or terminology. What remains limited is an explicit synthesis that links reported threshold indicators to dominant runoff mechanisms, event-scale mechanism transitions under increasing wetness, and recurring soil-geology-hydrogeology settings across catchments (James and Roulet, 2007; McGuire and McDonnell, 2010; Mirus and Loague, 2013; Ross et al., 2021; Scaife et al., 2020).Here, structural connectivity refers to relatively persistent catchment attributes that define potential flow-path architecture, such as soil depth, permeability contrasts, lithology, weathered or fractured bedrock, topography, and drainage organization. Functional connectivity refers to the event-scale activation of these pathways as rainfall interacts with antecedent wetness, storage, soil moisture, and groundwater level.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).~~

To address this gap, this study synthesizes reported nonlinear and threshold storm-runoff behavior across experimental catchments worldwide, linking threshold indicators, reported dominant runoff generation mechanisms, wetness-dependent mechanism transitions, and soil–geological-hydrogeology context within a common analytical framework.~~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.~~

Specifically, we address ~~the following~~three questions:

1. Which rainfall-based, state-based, or composite indicators are used in the literature to identify threshold-like storm-runoff responses?~~Is there a transferable rainfall–wetness indicator that consistently captures storm runoff regime shifts beyond rainfall-only metrics?~~
2. In studies that explicitly report wetness-dependent dominant mechanism transitions, which runoff pathways become active as catchment wetness, storage, soil moisture, or groundwater level increases?~~Do dominant runoff generation mechanisms follow systematic and directional evolution pathways as catchment wetness increases?~~
3. Which recurring soil–geology–hydrogeology settings are associated with different reported runoff mechanisms and their wetness-dependent activation?~~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?

Mechanism transitions here refer to changes in the mechanism dominating stormflow within the same catchment during events or event sequences as wetness increases; they are not inferred from climatic gradients or interannual change. Rather than seeking universal threshold values, this review focuses on recurring trigger-state-structure associations that help explain nonlinear runoff responses across diverse hydrological settings.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 investigate event-scale nonlinear and threshold-like runoff generation, we conducted a literature synthesis of peer-reviewed studies reporting rainfall–runoff nonlinearity, abrupt stormflow responses, or runoff threshold behavior across experimental catchments. The review focused on observational and process-based studies that explicitly linked threshold-like runoff responses to runoff generation mechanismsTo 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 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 the Web of Science Core Collection and Scopus for publications from database inception to 2024. Search terms combined concepts related to thresholds, nonlinearity, and runoff generation, including “runoff threshold”, “threshold behavior”, “nonlinear runoff”, “rainfall-runoff nonlinearity”, “stormflow threshold”, “runoff regime shift”, and “stormflow generation”, together with catchment-related terms such as “catchment”, “watershed”, “hillslope”, and “basin”. The search returned 745 records, including 344 from Web of Science and 401 from Scopus. After removing 292 duplicates, 453 unique records remained. All unique records were screened by title and abstract, followed by targeted full-text assessment when title and abstract information was insufficient. This screening identified 153 studies that met the inclusion criteria and provided catchment-scale information on threshold-like runoff behavior and runoff generation mechanisms.~~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, such as~~ (e.g.,~~ rainfall and runoff time series, hydrograph~~/~~ or hysteresis analyses, soil moisture or groundwater dynamics, tracers~~/~~ or isotopes, or similar process evidence), and (ii) ~~included an~~ explicitly interpretation of nonlinear or threshold-like runoff behavior~~, along~~ together with the associated dominant runoff generation mechanism(s). Studies were excluded if they focus only on approximately linear rainfall–runoff relationship, long-term water-balance analysis, or model simulations without event-scale observational evidence of threshold-like behavior.

~~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.~~ The 153 retained studies provided information for 176 experimental catchments. After excluding 39 catchments based solely on model simulations without direct field observations, the final synthesis dataset contained 138 experimental catchments. The catchment was used as the primary unit of synthesis. Publications reporting multiple catchments were separated into individual catchment records, whereas multiple publications on the same catchment were consolidated to avoid double counting. Additional publications for the same catchment were used only to supplement information on threshold indicators, runoff mechanisms, or catchment attributes.~~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, spanning diverse vegetation, soil, and geological settings, providing broad hydroclimatic coverage while maintaining a focus on event-scale runoff processes and nonlinear behavior.~~

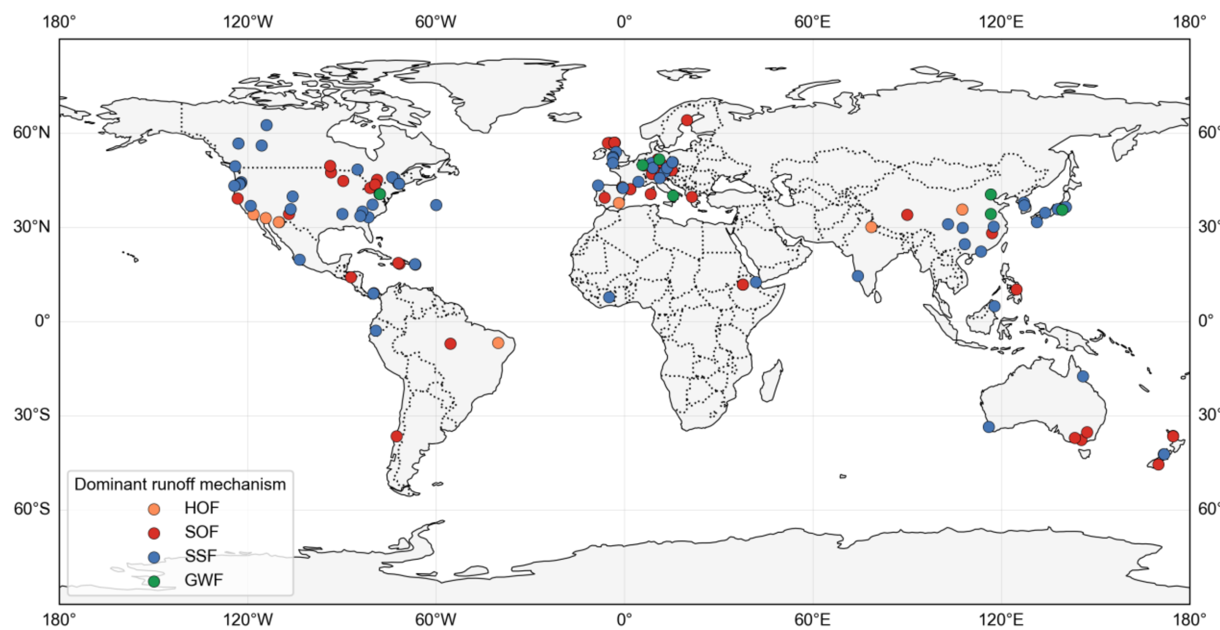


Figure 1. Global distribution of study catchments categorized by dominant runoff generation mechanisms. Colored symbols indicate the dominant or combined runoff generation mechanisms reported for each catchment, including ~~infiltration-excess overland flow (~~HOF~~)~~, ~~saturation-excess overland flow (~~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 harmonized into four main process classes and their combinations: Hortonian overland flow (HOF), saturation-excess overland flow (SOF), subsurface stormflow (SSF), and groundwater flow (GWF). Mechanism classes were extracted from the process interpretations reported in the original studies and were not inferred solely from climate, vegetation, soil, or geological descriptors.

HOF was assigned when the source study interpreted event runoff as infiltration-excess or Hortonian overland flow. SOF was assigned when stormflow was interpreted as saturation-excess overland flow, return flow, or runoff from saturated. SSF was assigned when the source study reported event-scale lateral subsurface flow through soil, regolith, preferential pathways, macropores, pipes, perched zones, or along restrictive layers such as the soil–bedrock interface. Although SOF and SSF can both contribute to flood discharge in stream channels, they were distinguished by the dominant reported flow pathway: SOF reaches the channel mainly as surface runoff from saturated areas, whereas SSF is transmitted mainly through lateral subsurface pathways before entering the channel. GWF was assigned only when the original study interpreted stormflow as including event-scale shallow groundwater responses within weathered bedrock or fractured regolith; it does not refer to regional confined aquifers or long-term groundwater baseflow.

Dominance refers to the mechanism interpreted by the source study as the primary contributor to stormflow during events exhibiting nonlinear or threshold-like behavior. It does not imply that only one runoff process operated in a catchment. Mixed categories, such as HOF–SOF, SOF–SSF, and SSF–GWF, were assigned when the original studies explicitly reported co-dominant mechanisms or event-dependent switching among mechanisms. These mixed categories were used for mechanism classification, whereas ordered wetness-dependent shifts were analyzed separately in the transition analysis only when the source study explicitly reported changes in the active or dominant mechanism during events or across event sequences.~~Runoff generation mechanisms were classified based on established process-based frameworks that distinguish surface- and subsurface-dominated stormflow pathways. Each 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

In this review, threshold behavior refers to an observed nonlinear runoff response pattern reported in the source studies, whereas dominant runoff mechanisms and hydrologic connectivity transitions are treated as process interpretations reported by the original authors or synthesized conceptually in this review. In this review, threshold behavior refers to an observed nonlinear runoff response pattern reported in the source studies, whereas dominant runoff mechanisms and hydrologic connectivity transitions are treated as process interpretations reported by the original authors or synthesized conceptually in this review. 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. Rainfall characteristics, including event rainfall amount, rainfall intensity, and rainfall duration, were treated as triggering conditions, whereas antecedent or within-event hydrological states were treated as variables that modulate the emergence of nonlinear runoff responses.

For the Sankey diagram in Fig. 3, each catchment record was coded using three linked fields: the reported dominant runoff generation mechanism, the hydrological state domain, and the threshold indicator used to identify or describe the nonlinear response. Hydrological state domains were harmonized into four categories: antecedent moisture condition, soil water content, groundwater level, and integrated storage state. AMC includes broad pre-event wetness descriptors such as antecedent precipitation, antecedent precipitation index, antecedent baseflow, or qualitative wet/dry catchment-state descriptions. Integrated storage state includes catchment storage, storage deficit, or explicitly coupled soil-moisture–groundwater conditions.

Reported threshold indicators were standardized into a limited set of categories, including event rainfall amount (P), rainfall intensity (Pi), antecedent precipitation index (API), soil water content or soil moisture (SWC), groundwater level or water-table depth (GWL), storage metrics, and composite rainfall–state indicators. When multiple threshold indicators were reported for the same catchment, the indicator identified by the source study as the primary threshold descriptor was retained. Link width in Fig. 3 represents the number of catchments reporting each mechanism–state-domain–indicator pathway.~~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 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 3.54. Because monitoring data availability differed substantially among catchments (e.g., rainfall–runoff observations only versus additional soil-moisture or groundwater measurements), this review synthesizes which indicators were reported in the literature but does not evaluate their comparative predictive or explanatory skill.

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 four operational categories: humid, semi-humid, semi-arid, and arid categories, based on climate type descriptions and , mean annual precipitation, and, where available, Köppen climate information reported in the source studies. Catchments described as humid, perhumid, tropical humid, or temperate humid were classified as humid; those described as sub-humid or semi-humid were classified as semi-humid; those described as semi-arid or dry steppe were classified as semi-arid; and those described as arid or desert were classified as arid. When source descriptions were ambiguous, mean annual precipitation and regional climate context were used to assign the closest category.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. Because the reviewed catchments are research catchments rather than a representative sample of the global land surface, aridity and vegetation classes were used to describe the composition of the reviewed literature, not to infer the global prevalence or absence of specific runoff mechanisms.

2.5 Soil–geology – hydrogeology ~~keyword~~ co-occurrence network

To examine recurring associations between dominant runoff generation mechanisms and subsurface characteristics, we conducted a soil–geology – hydrogeology keyword co-occurrence ~~network~~ analysis. This analysis identifies combinations of soil, geological, and hydrogeological ~~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 reported 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~~A2), 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 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 descriptors were used to construct mechanism–descriptor co-occurrence networks. In this analysis, co-occurrence refers to the presence of a given runoff generation mechanism and a standardized soil–geology–hydrogeology descriptor within the same independent catchment record. For each mechanism–descriptor pair, the co-occurrence frequency was calculated as the number of independent catchments in which both the mechanism and descriptor were reported. Repeated mentions within the same catchment, or multiple publications describing the same catchment, were counted only once. In the networks, colored nodes represent runoff mechanism classes, gray nodes represent standardized descriptors, and links represent mechanism–descriptor co-occurrences. Link thickness is proportional to the number of independent catchments supporting each mechanism–descriptor link. To reduce the influence of isolated case studies, only mechanism–descriptor links reported in at least two independent catchments were retained in the main network.~~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.~~ As a sensitivity check to the minimum co-occurrence threshold, we reconstructed the networks using thresholds of three, four, and five independent catchments. The main mechanism-specific associations remained qualitatively similar~~Sensitivity tests with stricter co-occurrence thresholds (≥3 catchments) showed similar structural clusters~~, indicating that the identified fingerprints are not driven by isolated cases.

2.6 Software and reproducibility

Data extraction and initial standardization were performed in Microsoft Excel, followed by data processing and visualization in Python using the PyCharm integrated development environment [2024.2]. Data cleaning, frequency analysis, and transition-matrix construction were conducted using pandas and NumPy. Sankey diagrams were generated with Plotly, co-occurrence networks were constructed using NetworkX and visualized with Matplotlib, and transition-probability heatmaps were produced using Seaborn. Global catchment maps were generated with Cartopy, using Natural Earth base layers to display coastlines, national borders, and land features.

3. Results

3.1 Reported dominant mechanisms, state variables, and threshold indicators~~state variables and indicators of runoff threshold behavior~~

Across the 138 reviewed catchments, subsurface- and saturation-related mechanisms were most frequently reported (Fig. 2). SSF was 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. In contrast, HOF accounts for less than 10% of the reviewed catchments. GWF and categories involving groundwater represent a smaller fraction of the dataset.

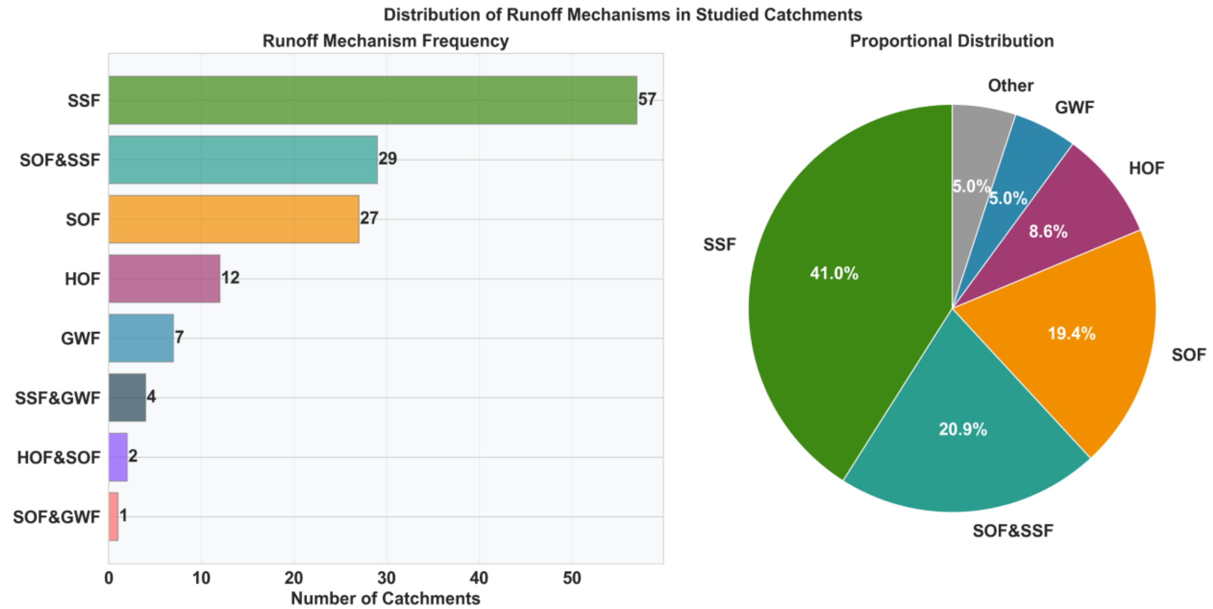


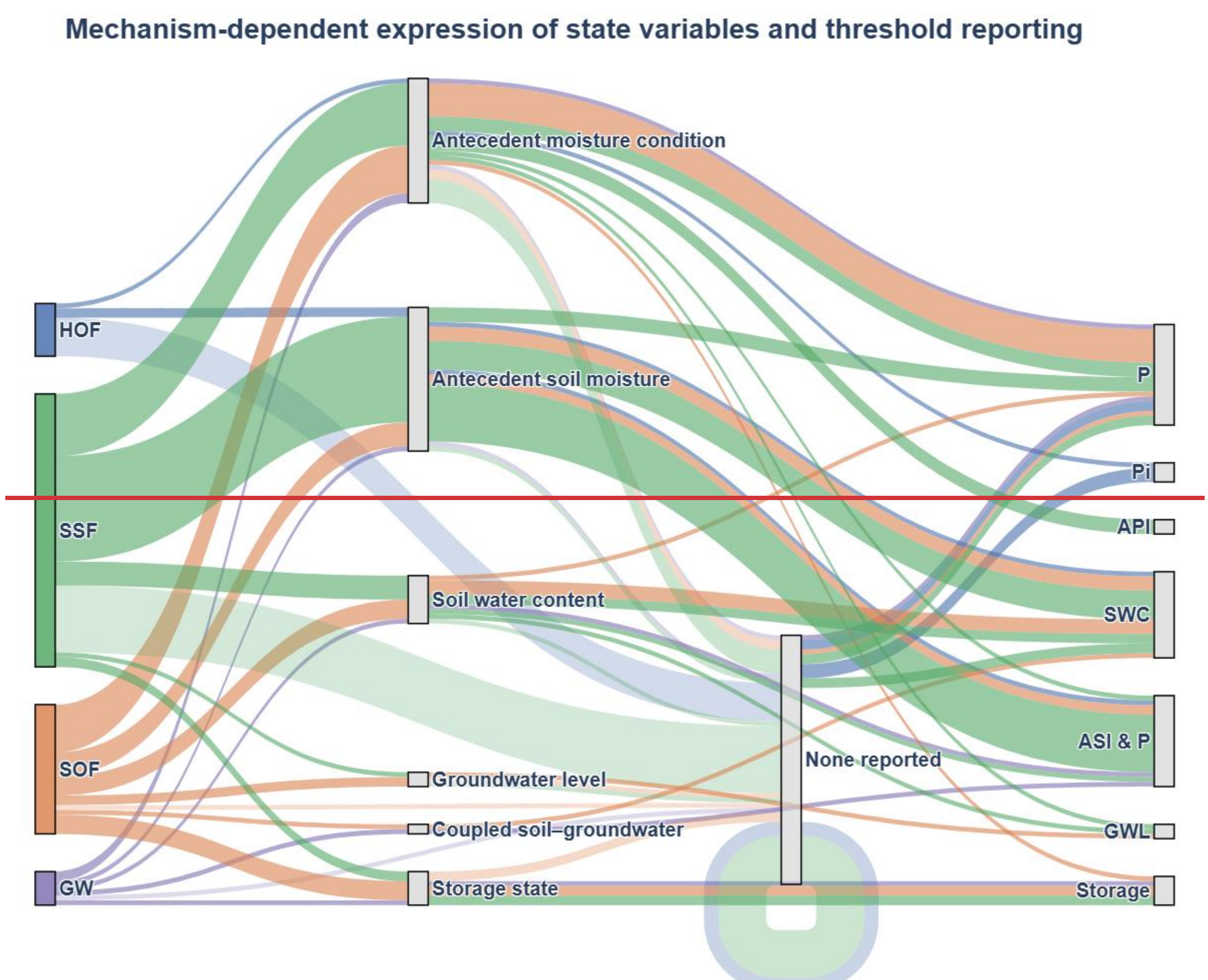
Figure 2. Frequency and proportional contribution of reported dominant runoff generation mechanisms in the reviewed catchments. The left panel shows the number of catchments classified under each dominant mechanism or mechanism combination, based on the primary interpretation in the original studies. The right panel shows the proportional contribution of each mechanism category to the full catchment dataset. Percentages are calculated relative to all reviewed catchments (n = 138), with each catchment counted once.

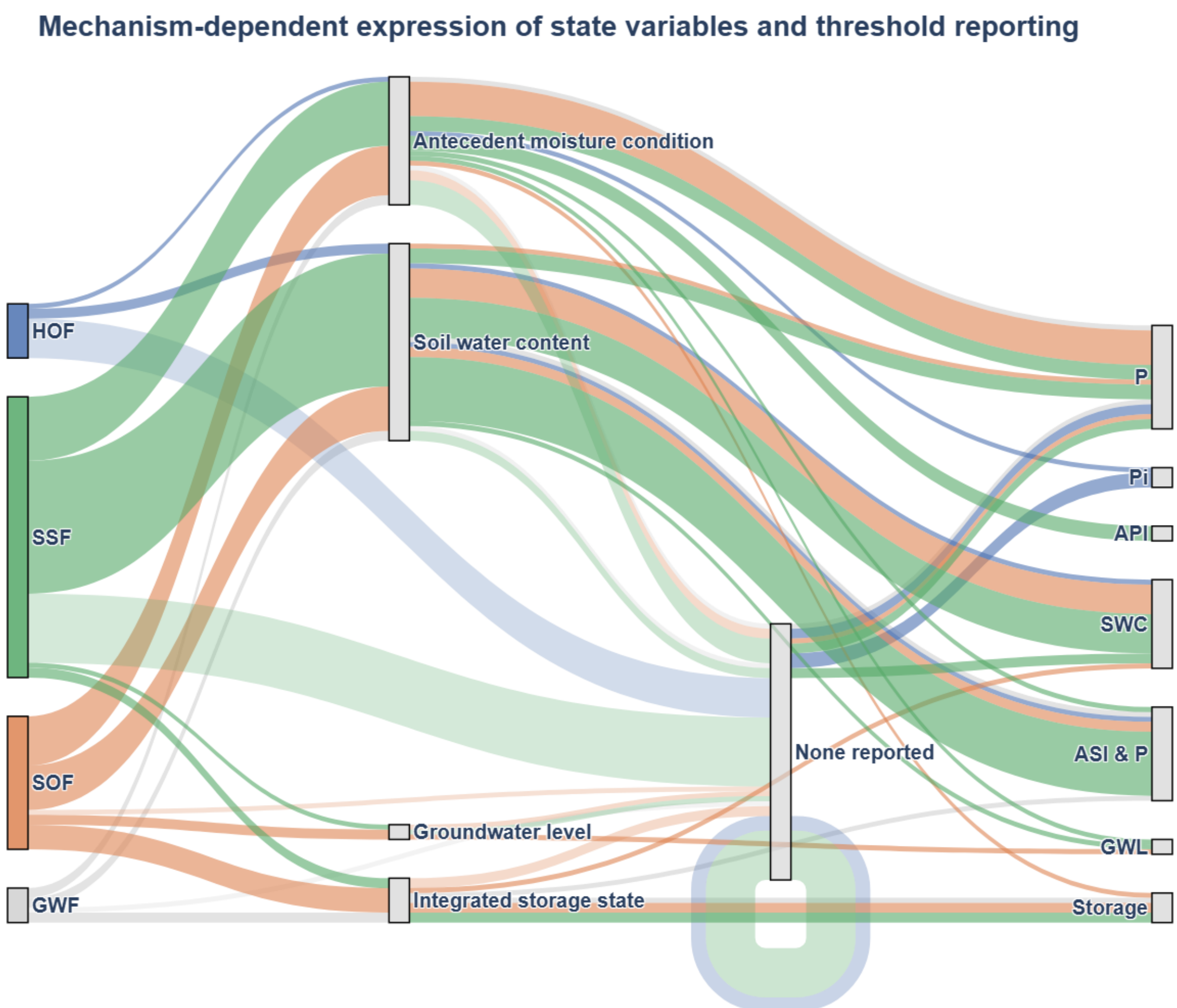
~~This section summarizes how nonlinear runoff threshold behavior has been reported in the reviewed literature, focusing on the state variables and indicators used, rather than on process interpretation.~~

~~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.~~

Figure 3 summarizes how reported threshold indicators vary among these mechanism classes. HOF-dominated catchments more often used rainfall-based descriptors, such as event rainfall amount or rainfall intensity, whereas SOF-, SSF-, and GWF-dominated catchments more often reported antecedent wetness, soil moisture, storage-related variables, groundwater level, or composite rainfall–state indicators.

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 water content, groundwater level, and integrated storage state ~~soil or catchment storage state, groundwater level, and coupled soil–groundwater metrics~~. Similarly, indicators used to identify nonlinear runoff behavior include rainfall-based variables, state-based variables, and composite indicators combining rainfall and antecedent wetness information. In some studies, no explicit quantitative indicator was reported, and threshold behavior was described qualitatively.~~The relative frequency of these variables varies among dominant runoff mechanisms, as illustrated in Fig. 2.~~





Mechanism-dependent expression of state variables and threshold reporting
HOF
SSF
SOF
GWF
Antecedent moisture condition
Soil water content
Groundwater level
Integrated storage state
None reported
P
Pi
API
SWC
ASI & P
GWL
Storage

Figure ~~2~~3. Sankey diagram summarizing reported trigger–state indicators used to identify nonlinear runoff threshold behavior across dominant runoff generation mechanisms. Rectangular node height is proportional to the number of catchments. P, event rainfall amount; Pi, rainfall intensity; API, antecedent precipitation index; SWC, soil water content or soil moisture; GWL, groundwater level; Storage, catchment storage. Nodes on the left represent dominant runoff mechanisms, ~~the~~ middle nodes represent hydrological state variables, and ~~the~~ right nodes represent the reported threshold indicators used to identify threshold behavior. Flow bands connect mechanisms, state variables, and indicators, with band width proportional to the number of reviewed catchments~~studies~~ reporting each combination. The “None reported” node indicates reviewed catchments for which the source studies described nonlinear or threshold-like runoff responses but did not specify the corresponding variable or indicator. Specifically, 29 catchments did not report an explicit state variable, and 41 catchments did not report an explicit threshold indicator.~~The node "None reported" indicates studies that described nonlinear runoff responses without specifying an explicit threshold indicator.~~

Overall, Figs. 2 and 3 show that the reviewed literature is dominated by subsurface- and saturation-related runoff mechanisms, but that the variables used to identify threshold-like behavior differ substantially among mechanism classes. This variability highlights the need to distinguish reporting frequency from indicator performance: the greater use of state-based indicators in SOF-, SSF-, and GWF-related studies reflects how thresholds have been reported in the literature, not a formal comparison of explanatory power among indicators.~~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 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.

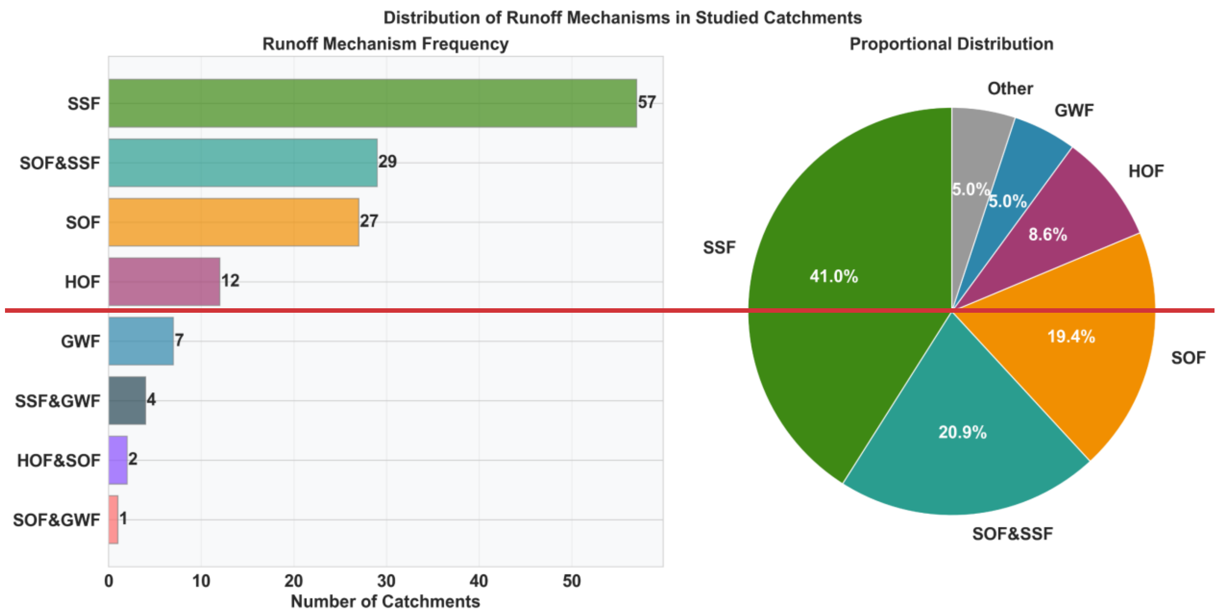


Figure 3. Frequency and proportional contribution of dominant runoff generation mechanisms reported in the reviewed catchments. The left panel shows the number of catchments classified under each dominant runoff mechanism or reported mechanism combination, based on the primary interpretation in the original 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 2 Distribution of reported dominant mechanisms across aridity and vegetation classes

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 within the reviewed catchment sample. These counts describe the composition of the compiled literature dataset and should not be interpreted as estimates of the global prevalence of runoff mechanisms across climate or land-cover classes. Stacked bar charts show the number of reviewed catchments with each reported dominant mechanism within four operational climatic wetness aridity classes (humid, semi-humid, semi-arid, and arid) and across major vegetation types. Single and combined mechanisms are shown separately.

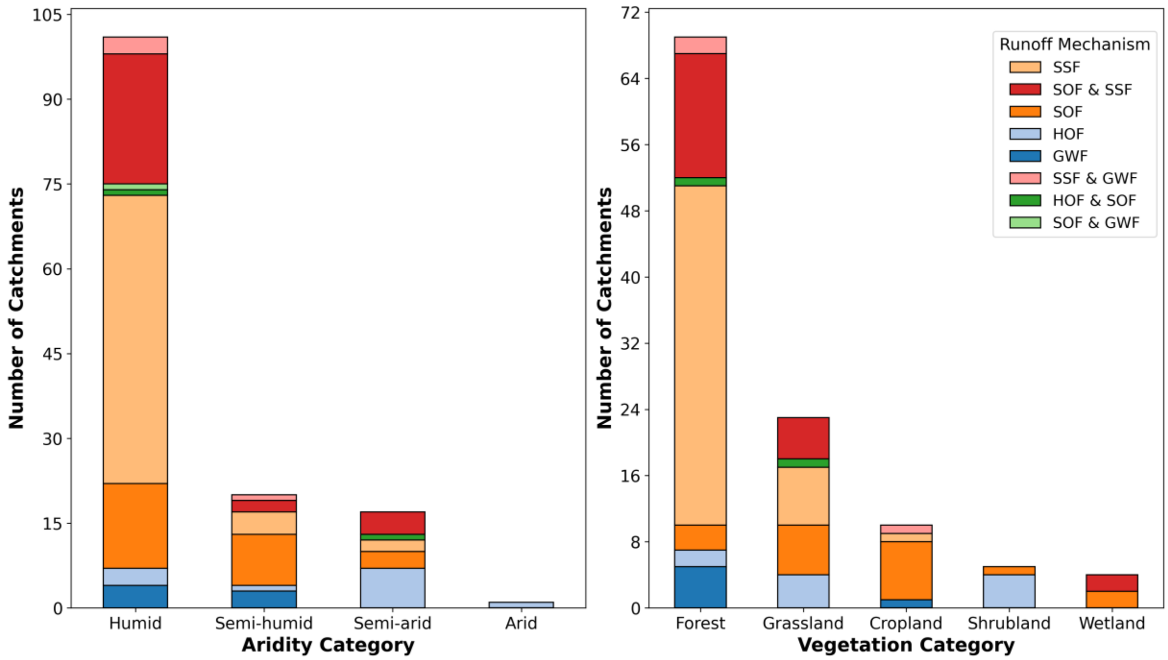


Figure 4. Distribution of dominant runoff generation mechanisms across aridity and vegetation categories. Bars show the number of catchments in each aridity or vegetation class, with each catchment counted once.

Within the reviewed dataset~~Across the aridity gradient~~ (Fig. 4a), humid catchments constitute the largest subset and therefore include~~account for the majority of observations and exhibit~~ the widest range of reported runoff generation mechanisms. Among these humid catchments, SSF is the most frequently reported mechanism,~~represents the largest share,~~ followed by SOF and combined SOF–SSF mechanisms. Groundwater-related mechanisms (GWF and SSF–GWF) are represented mainly by~~almost exclusively reported in~~ humid catchments in this dataset. Semi-humid catchments are fewer in number and most commonly report~~and are dominated by~~ SOF, with additional cases of~~contributions from~~ SSF and GWF. In the semi-arid subset~~catchments~~, the total number of catchments~~reported systems~~ is smaller; SSF and SOF are still represented~~remain~~, while~~but~~ HOF accounts for~~constitutes~~ a larger proportion of the reviewed semi-arid cases~~relative to wetter classes~~. The single arid catchment included in the dataset was~~Only one arid catchment is included,~~ classified as HOF-dominated.

Vegetation-related patterns should be interpreted even more cautiously because the reviewed catchments are strongly uneven across land-cover classes~~Mechanism distributions also vary across vegetation types~~ (Fig. 4b). Forested catchments are overrepresented in the dataset and include ~~the most frequent, representing~~ a mix of SSF, SOF, SOF–SSF combinations, and groundwater-related mechanisms. Grassland catchments show a mixture of reported 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. The vegetation patterns in Fig. 4b describe where threshold-related runoff mechanisms have been reported in the reviewed literature, rather than the global prevalence of those mechanisms across land-cover classes.

~~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.~~

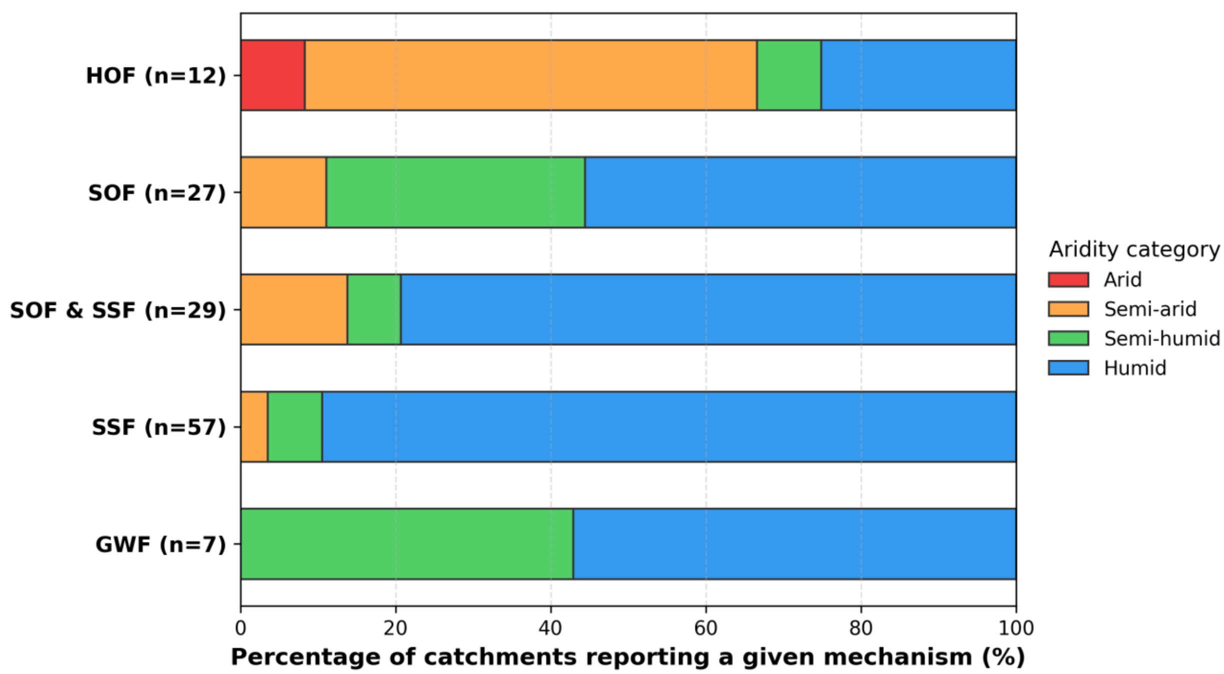


Figure 5. Distribution of aridity for the catchments for which each dominant runoff generation mechanism was reported~~Climatic composition of dominant runoff generation mechanisms (percentages relative to mechanism-specific sample size)~~. Percentages are calculated relative to the total number of catchments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

Among the reviewed catchments classified as SSF or SOF–SSF, most are located in humid climates, with smaller numbers from semi-humid and semi-arid regions. Reviewed SOF-dominated catchments are distributed across humid and semi-humid climates, with some occurrences in semi-arid environments. HOF-dominated catchments occur across the climatic wetness classes represented in the dataset, with the largest proportion among the semi-arid cases. Reviewed GWF-dominated catchments are represented only by humid and semi-humid catchments in this dataset; this absence from the semi-arid and arid subsets should not be interpreted as evidence that groundwater-related runoff responses cannot occur in drier regions.

Overall, Fig. 5 suggests a climate-related shift in the reported depth domain of active runoff pathways. Drier subsets are relatively more represented by surface-dominated responses, whereas humid and semi-humid subsets include more SSF-, SOF–SSF-, and GWF-related responses, which are commonly linked to deeper soil wetting, regolith storage, shallow groundwater rise, or weathered-bedrock connectivity. This pattern reflects the composition of the reviewed catchment literature and should be interpreted as a synthesis tendency rather than a universal climatic sequence.~~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 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~~3 Reported event-scale transitions in dominant runoff generation mechanisms within catchments~~Transitions of dominant runoff generation mechanisms under increasing wetness~~

We synthesized evidence from 23 experimental catchments where source studies explicitly reported changes in the dominant runoff generation mechanism within the same catchment during storm events or across event sequences as catchment wetness increased. In this section, “mechanism transitions” refer to changes in the mechanism that dominates stormflow under different event wetness, storage, soil-moisture, or groundwater conditions. These transitions do not imply that the catchment's structural runoff potential changes during an event; rather, they indicate that different pre-existing runoff pathways become activated and dominate stormflow as functional connectivity develops.~~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~~ The most frequently reported initial mechanisms are HOF and SOF, and the dominant transitions generally proceed from surface-dominated responses toward SOF, SSF, or groundwater-influenced responses.~~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.~~

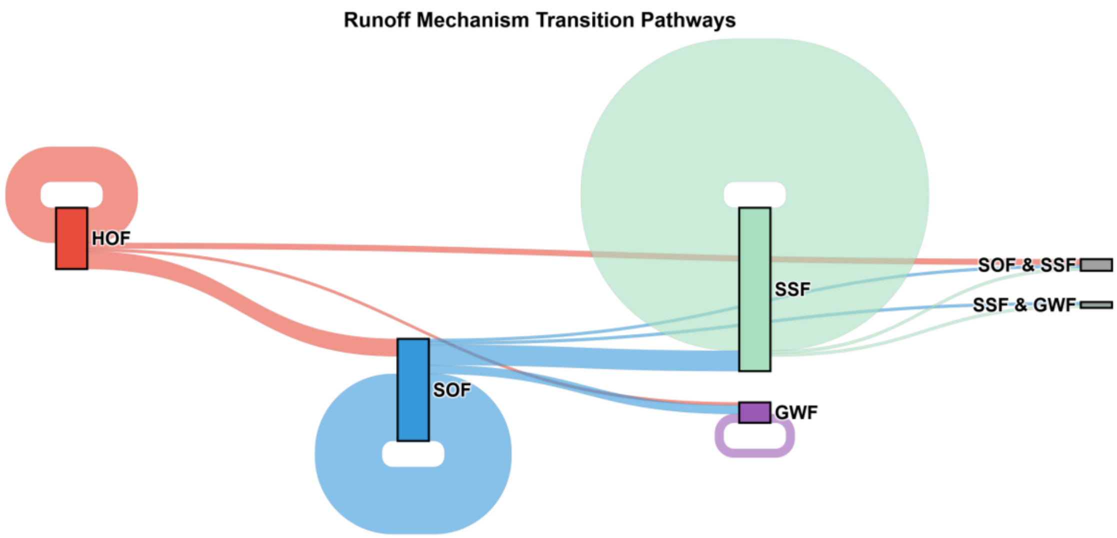


Figure 6. Sankey diagram illustrating reported runoff-mechanism transition pathways under increasing catchment wetness.observed transition pathways of dominant runoff generation mechanisms under increasing wetness. The diagram includes only catchments with explicitly reported wetness-dependent mechanism shifts or persistence. Rectangular node height is proportional to the number of catchments with each initial mechanism. Directed band width is proportional to the number of catchments reporting each transition. Colored self-loop bands around a node indicate cases where the reported dominant mechanism remained unchanged under wetter conditions. 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. Catchments initially dominated by HOF typically shiftedFor catchments initially dominated by HOF, transitions typically occur toward SOF (29), combined SOF–SSF responses (10%), and less frequently, groundwater-dominated flow (5%). Catchments initially dominated by SOF shifted towardtransition to SSF (20%), GWF (9%), and mixed SOF–SSF (3%) and SSF–GWF responses (3%). Transitions originating from SSF are were less frequently reported, but include shifts toward SOF–SSF (4%) and SSF–GWF (2%).combined subsurface- and groundwater-dominated mechanisms.

Figure 7 further shows that the most common reported transitions originate from HOF and SOF, with transitions toward SOF and SSF being more frequent than reverse transitions. This pattern supports a tendency, within the event-scale transition subset, for the reported dominant active runoff pathway to shift from surface-dominated responses toward subsurface- or groundwater-influenced responses as catchment wetness, storage, soil moisture, or groundwater level increases.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%).

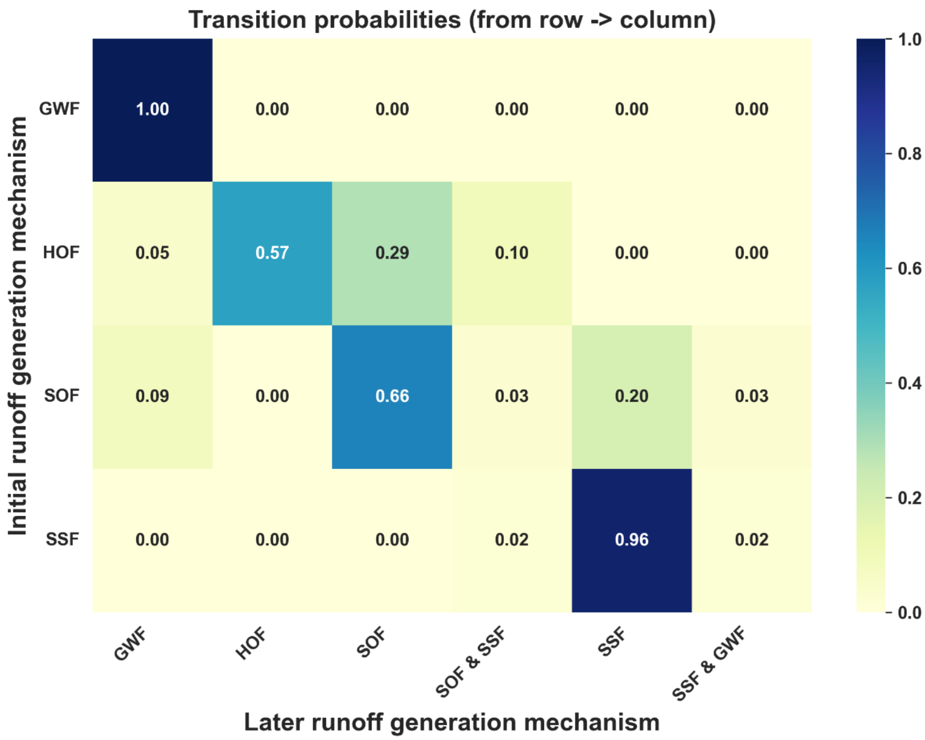


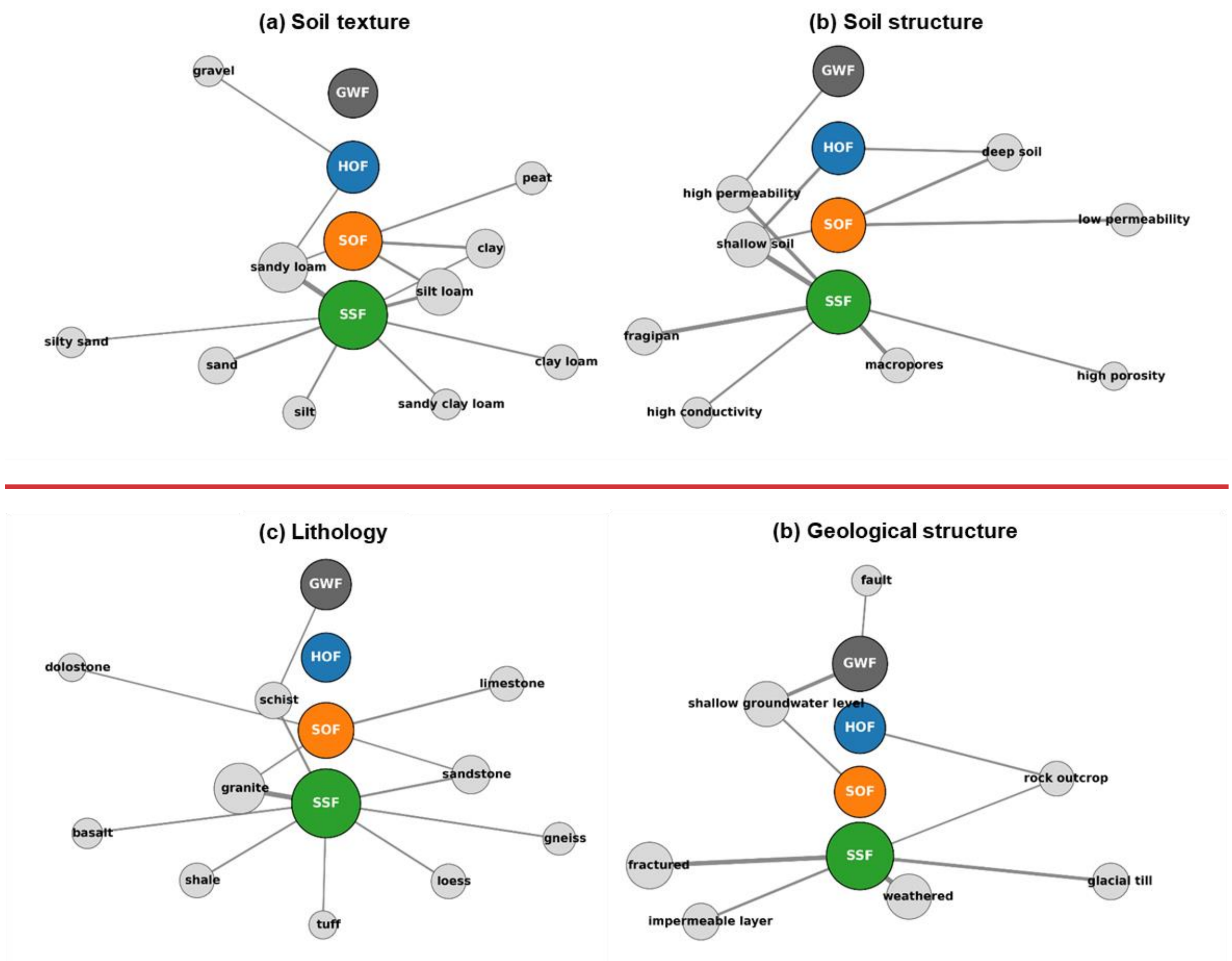
Figure 7. Conditional transition probabilities between dominant runoff generation mechanisms under increasing wetness. Values represent the proportion of catchments with a given initial mechanism (rows) that transitioned to each subsequent mechanism (columns). Transition probabilities were calculated using catchments as the unit of analysis; each row is normalized by the number of catchments with the corresponding initial dominant mechanism.

Within the transition subset, reported event-scale shifts more frequently proceeded from surface-dominated responses toward subsurface- or groundwater-influenced responses than in the reverse direction.~~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 used a one-sided Monte Carlo randomization test under a uniform transition-probability null model. We tested this directional tendency using a one-sided Monte Carlo randomization test under a uniform transition-probability null model, in which later mechanisms were randomly assigned with equal probability within each initial-mechanism class. The observed number of surface-to-subsurface or groundwater-influenced transitions was significantly higher than expected under the null model ($p < 0.05$).~~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 4 Soil–geology fingerprints of runoff generation mechanisms

Figure 8 summarizes mechanism–descriptor co-occurrence patterns, where links indicate that a runoff mechanism and a standardized soil–geology–hydrogeology descriptor were reported for the same independent catchment.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 (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. Here, “structural fingerprints” refer to recurring co-occurrence patterns between reported dominant runoff mechanisms and standardized soil, geological, and hydrogeological descriptors, rather than deterministic soil–geology controls. HOF-dominated catchments in the reviewed literature were recurrently associated with rock outcrops, shallow soils, gravel, sandy loam, and, in fewer cases, deep soils. These descriptors should be interpreted as co-occurring structural settings rather than as individual causal controls. In particular, shallow soils and rock outcrops likely represent thin or discontinuous soil cover and limited effective near-surface storage, whereas the occurrence of deep soils in some HOF cases indicates that HOF cannot be attributed solely to limited soil depth or storage.


(a) Soil texture
gravel
GWF
HOF
peat
SOF
clay
sandy loam
silt loam
SSF
silty sand
sand
clay loam
silt
sandy clay loam
(b) Soil structure
GWF
HOF
deep soil
high permeability
SOF
low permeability
shallow soil
SSF
fragipan
macropores
high porosity
high conductivity
(c) Lithology
GWF
HOF
dolostone
limestone
schist
SOF
sandstone
granite
SSF
basalt
gneiss
shale
loess
tuff
(b) Geological structure
fault
GWF
shallow groundwater level
HOF
rock outcrop
SOF
SSF
fractured
glacial till
weathered
impermeable layer

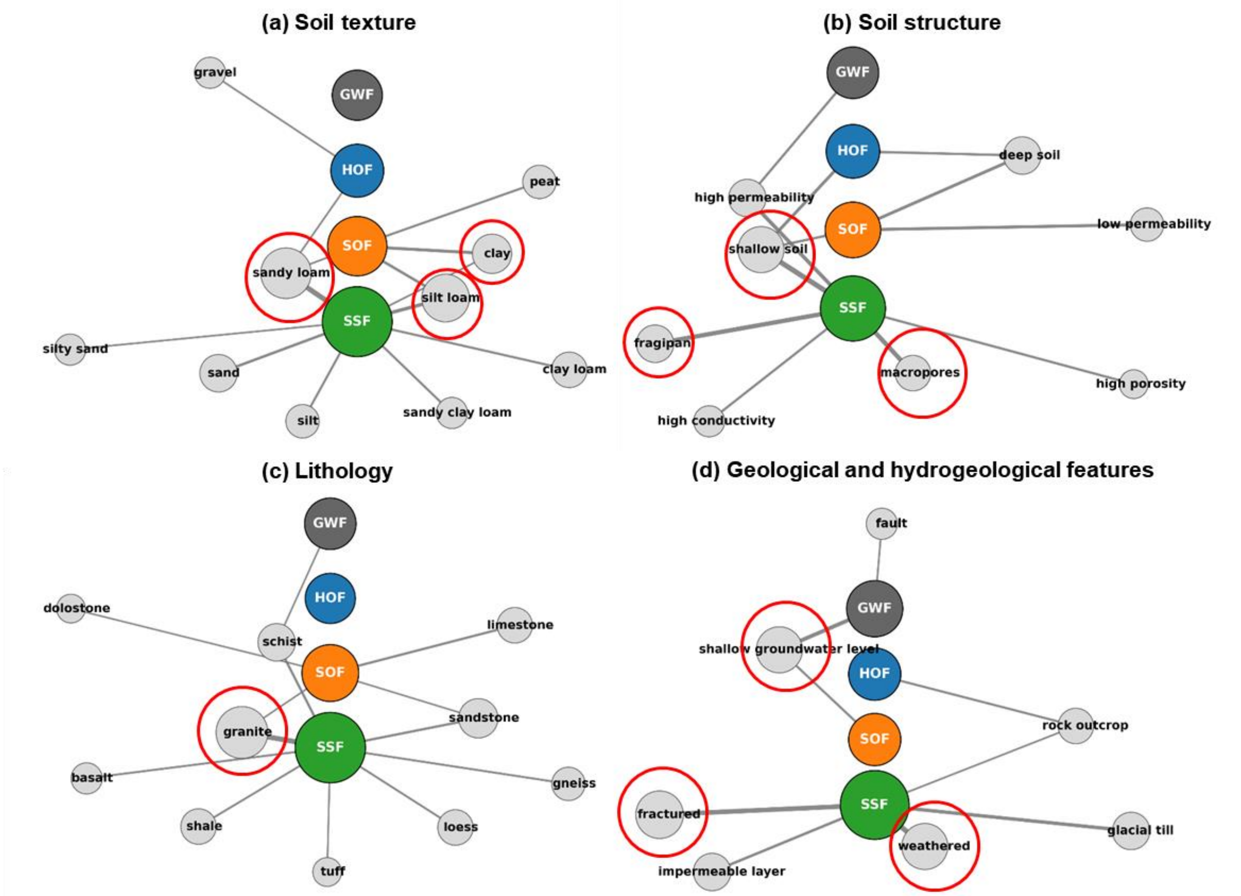


Figure 8. Soil–geology – hydrogeology fingerprints of dominant runoff generation mechanisms. Panels show co-occurrence relationships with (a) soil texture, (b) soil structural properties, (c) lithology, and (d) geological and hydrogeological features~~geological structure~~. Colored nodes represent dominant runoff mechanisms—HOF, SOF, SSF, and GWF—while gray nodes represent soil or geological descriptors~~keywords~~ extracted from the literature. A co-occurrence means that a given mechanism and descriptor were reported for the same independent catchment. Node size reflects the number of independent catchments in which a mechanism or descriptor was reported. Link thickness represents the number of independent catchments in which a given mechanism–descriptor pair co-occurred; repeated publications on the same catchment were counted only once. Networks were constructed from the subset of catchments with clearly reported dominant mechanisms and sufficient soil–geology–hydrogeology descriptors (n = 103). ~~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.~~

~~SOF exhibits a more distinct and coherent pattern of soil and geological associations. S~~There are strong co-occurrence links ~~connect~~ between SOF ~~to~~ and 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 as a hydrogeological condition, and with~~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~~. The absence of strong GWF links to limestone or granite in this network should not be interpreted as evidence that groundwater or shallow bedrock flow does not contribute to storm runoff in those lithologies. Rather, it indicates that event-scale groundwater flow was not reported as a dominant or combined mechanism in enough independent catchments with those descriptors to form a retained network link. In limestone or granite catchments, groundwater contributions may depend strongly on additional structural and hydrogeological features, such as karst development, fractures, weathered zones, shallow water tables, and hillslope–stream connectivity.

Overall, the four co-occurrence networks (Fig. 8) 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, "runoff threshold" is consistently used to describe nonlinear stormflow responses (Meerveld and McDonnell, 2017; Nanda and Safeeq, 2023; Nanda and Sen, 2021; Ross et al., 2021; Wang et al., 2022), yet Section 3.1 shows that these thresholds are reported with heterogeneous rainfall-based, state-based, storage-based, groundwater-based, and composite indicators. This heterogeneity reflects differences in monitoring design, available data, and process interpretation, and it limits direct comparison of threshold values across catchments.~~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.~~

The review does not show that rainfall-only indicators are inherently insufficient; rather, it shows that antecedent-state and composite indicators were more frequently reported than rainfall-only metrics. Many source studies interpreted threshold-like responses as rainfall interacting with soil wetness, storage, groundwater rise, saturation expansion, lateral subsurface flow, or hillslope–channel coupling~~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 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; Scaife et al., 2020; Tromp-van Meerveld and McDonnell, 2006a, b). This interpretation is consistent with earlier reviews that framed runoff thresholds as emergent outcomes of storage filling and connectivity activation. Ross et al. (2021) emphasized the widespread occurrence and typology of threshold behavior across contrasting environments, whereas McDonnell et al. (2021) used the fill-and-spill concept to organize runoff generation observations around storage activation and flow-path connectivity. The present synthesis builds on these perspectives by linking reported threshold indicators to dominant runoff mechanisms, event-scale mechanism transitions, and recurring soil–geology–hydrogeology settings across the reviewed catchments.

~~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.

Hydrologic connectivity is therefore used here as a conceptual organizing framework, not as a directly measured universal index across the reviewed studies. Although recent work has advanced process-based quantification of subsurface hydrological connectivity and its coupling with structural connectivity (Tromp-van Meerveld and McDonnell, 2006b; Zhang et al., 2026), most studies included in this review inferred connectivity-related threshold behavior from observable proxies such as antecedent precipitation, soil moisture, storage state, groundwater level, saturated-area expansion, or reported mechanism changes (Detty and McGuire, 2010; Penna et al., 2011; Scaife et al., 2020; Tromp-van Meerveld and McDonnell, 2006a). This distinction also separates event-scale runoff thresholds from relatively stable catchment storage-capacity parameters used in conceptual models. Catchment storage architecture may be treated as a structural property, whereas the rainfall amount or intensity required to trigger nonlinear runoff depends on antecedent storage deficit, soil moisture, groundwater level, API, and event rainfall characteristics, as shown for humid forest stormflow responses by (Zhang et al., (2021).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.

Together, these findings support comparison based on reported indicator types, state proxies, and associated mechanism changes, rather than on a single numeric threshold value or a directly quantified connectivity metric. Antecedent soil moisture, catchment storage, and groundwater level were among the most commonly reported state descriptors for SOF-, SSF-, and groundwater-influenced responses (Farrick and Branfireun, 2014; Nanda and Safeeq, 2023; Oswald et al., 2011; Penna et al., 2010; Saffarpour, 2016; Scaife et al., 2020). In HOF-related cases, rainfall intensity was more often reported as the immediate trigger, but connected surface runoff also depends on soil-vegetation-root systems, surface condition, crusting or compaction, macroporosity, microtopography, and vegetation cover(Gao et al., 2024).

~~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 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 reported ~~runoff~~ threshold behavior across mechanisms and catchments reflect interactions among rainfall forcing, antecedent state, and structural connectivity. Structural connectivity is shaped by vegetation cover and roots, soil texture and structure, macroporosity, soil depth, permeability contrasts, lithology, weathering, fractures, topographic convergence, and groundwater setting (Zehe and Sivapalan, 2009); these properties define potential storage and flow paths (Spence, 2010), whereas event wetness determines which pathways become functionally connected (Blume and Van Meerveld, 2015).

The soil-geology-hydrogeology fingerprints identified in Section 3.4 should be read as recurrent co-occurrence patterns rather than deterministic controls. Shallow rocky or discontinuous soils may reduce effective near-surface storage and support rapid surface runoff under intense rainfall, while fine-textured soils, peat, low-permeability layers, shallow groundwater, or convergent topography may promote near-surface saturation and SOF (Devito et al., 2023; Jencso and McGlynn, 2011; de Moraes et al., 2006; Penna et al., 2010; Sidle et al., 2000). Permeability contrasts, macropores, fractured or weathered bedrock, and soil-bedrock interfaces may support SSF or shallow-groundwater-influenced stormflow when sufficiently connected (Blume and Van Meerveld, 2015; Detty and McGuire, 2010; Sidle et al., 2000; Zhang et al., 2021). These associations are context dependent. Coarse materials do not inherently imply low infiltration (Dunne and Black, 1970), and low-permeability conditions can contribute to either HOF or SOF depending on whether the limitation occurs at the surface or below a more permeable layer (de Moraes et al., 2006). Thus, Fig. 8 provides structural contexts for interpreting reported mechanisms, not one-to-one causal assignments.

The climatic and vegetation patterns in Section 3.2 should also be interpreted cautiously because the reviewed catchments are not a representative sample of the global land surface. Humid and forested experimental catchments are overrepresented, whereas dryland, cropland, urban, and suburban systems are underrepresented or absent. In SOF-related settings, rainfall intensity and profile structure can also modify storage behavior and the onset of saturation-excess runoff (Zhang et al., 2022). The results nevertheless align with recent global syntheses showing that runoff processes are shaped by environmental context. McMillan et al. (2025) emphasized the roles of aridity, terrain, and biomes in organizing flow pathways, and Penna (2026) highlighted interacting climatic, hydrological, pedological, vegetational, geological, and geomorphological controls in forested catchments. Our contribution is narrower and threshold-focused: it links reported threshold indicators to dominant mechanisms, event-scale mechanism transitions, and recurring structural associations.

Climate, vegetation, soil development, and rock weathering should therefore be interpreted as coupled controls. Climate influences long-term vegetation cover, weathering intensity, regolith thickness, soil structure, and groundwater storage (Zehe and Sivapalan, 2009); these properties shape structural connectivity (Devito et al., 2023), while event rainfall and antecedent wetness regulate functional connectivity during storms (Blume and Van Meerveld, 2015). The greater representation of HOF in drier subsets and of SSF, SOF-SSF, and GWF in humid or semi-humid subsets is consistent with a climate-conditioned shift in the reported depth domain of active pathways, but it should be viewed as a broad reporting tendency rather than a universal HOF-to-GWF sequence. 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 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.~~

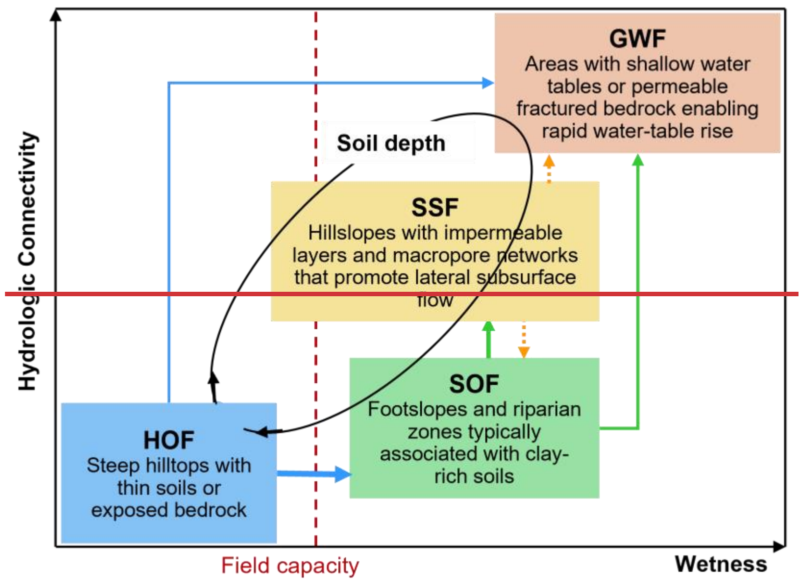
~~It should be noted that humid catchments are overrepresented in the reviewed dataset, potentially biasing the apparent dominance of subsurface and groundwater transitions. While directional reorganization remains evident within individual aridity classes, the limited number of arid and semi-arid systems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

4.3 A revised conceptual framework for storm runoff generation

Building on these results, Fig. 9 presents a conceptual, non-metric framework for event-scale transitions in the dominant runoff mechanism within catchments. The y-axis represents the vertical integration or depth extent of active flow paths contributing to event runoff, not total hydrologic connectivity in all directions. Thus, the figure does not imply a universal ranking of connectivity or a climatic sequence among catchments.

Within this framework, runoff thresholds are response conditions arising from interactions among rainfall forcing, catchment state, and structural constraints (Sidle et al., 2000). This review does not evaluate threshold stationarity within individual catchments through time, and the framework should be interpreted as a synthesis of reported indicators, mechanisms, and structural contexts rather than a quantitative model~~the global synthesis of thresholds, mechanism distributions, 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 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)..



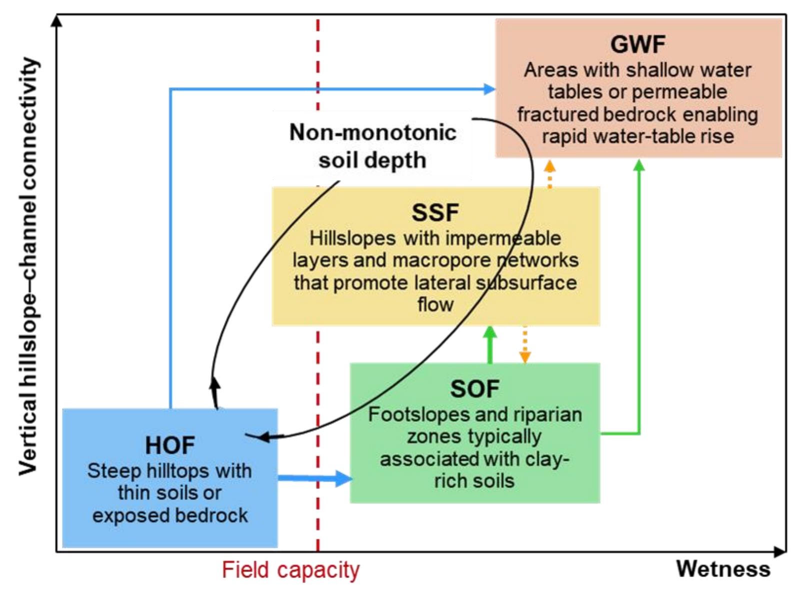


Figure 9. Conceptual framework of event-scale runoff mechanism transitions across gradients of wetness and vertical flow-path integration. The x-axis represents increasing antecedent and within-event wetness or storage state. The y-axis represents the conceptual vertical integration or depth extent of activated flow paths contributing to event runoff, rather than total hydrologic connectivity in all directions. The SSF box spans both sides of the field-capacity reference to indicate that subsurface stormflow may occur below field capacity where preferential or interface flow pathways are active. Solid arrows indicate commonly reported within-catchment transition pathways as event wetness increases, with arrow thickness representing relative reporting frequency in the compiled transition subset. Dashed arrows denote less frequent or context-dependent pathways, including SSF-to-SOF transitions where lateral subsurface flow exfiltrates in footslopes, valley floors, or riparian zones, and SSF-to-GWF transitions where continued wetting connects lateral subsurface flow with shallow groundwater, weathered regolith, or fractured bedrock pathways. The red dashed line indicates an approximate field-capacity reference, not a universal runoff-initiation threshold. The soil-depth arrow represents a non-monotonic structural control: very shallow soils or rock outcrops may favor HOF because of limited effective storage, whereas very deep and dry profiles may also remain HOF-dominated during extreme rainfall because subsurface storage and groundwater connectivity thresholds are difficult to reach. 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.

Mechanism transitions in this framework refer only to reported within-catchment changes in the mechanism dominating stormflow during events or event sequences as wetness increases (Chittolina et al., 2023; Detty and McGuire, 2010; Meyles et al., 2003; Penna et al., 2011; Tromp-van Meerveld and McDonnell, 2006a, b, a). They do not imply that the vegetation-soil-geology structure changes during an event; rather, different pre-existing pathways become functionally connected as storage fills, saturated areas expand, preferential pathways activate, or shallow groundwater rises. This distinction separates within-catchment event-scale transitions from cross-catchment environmental patterns. Cross-catchment patterns describe differences in structural setting and reported mechanism occurrence among climatic wetness classes and soil-geology-hydrogeology contexts; they are not treated as temporal transitions.

The framework also allows non-monotonic and context-dependent pathways. SSF can occur below field capacity where macropores, pipes, perched zones, or soil-bedrock interfaces are active (Detty and McGuire, 2010; Kim, 2009; Saffarpour, 2016; Scaife et al., 2020; Scaife and Band, 2017); SSF may feed SOF where lateral subsurface flow exfiltrates in footslopes or riparian zones

(M. Srinivasan et al., 2002; Penna et al., 2011; Saffarpour, 2016); and very deep dry profiles, such as some arid loess catchments, may remain HOF-dominated because subsurface or groundwater connectivity is difficult to activate (Scaife and Band, 2017). For applications, measurable proxies such as rainfall intensity, API, soil moisture, storage deficit, groundwater level, saturated-area expansion, and structural descriptors are more practical than direct quantification of hydrologic connectivity. State-dependent switching functions in models may therefore be useful, but this review supports them as a conceptual outlook rather than a tested modeling result. ~~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 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.

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 review synthesizes reported storm-runoff threshold behavior across 138 experimental catchments by examining event-scale observations, threshold indicators, dominant runoff mechanisms, mechanism transitions, and soil-geology-hydrogeology context. The reviewed literature does not support a single universal threshold metric or directly transferable numeric threshold value across catchments; instead, reported thresholds are best interpreted through rainfall-state-structure combinations. ~~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.~~

Antecedent-state and composite indicators were more frequently reported than rainfall-only descriptors, but this reporting pattern should not be interpreted as a formal comparison of explanatory performance. In catchments with explicit event-scale transition evidence, the mechanism dominating stormflow commonly shifted from surface-dominated responses toward saturation-, subsurface-, or shallow-groundwater-influenced pathways as wetness increased.

Recurring soil-geology-hydrogeology associations provide structural context for these patterns by indicating potential storage and flow-path architecture, while event wetness controls which pathways become functionally connected. Future work should prioritize high-frequency observations of soil moisture, groundwater, saturated areas, and subsurface connectivity, together with clearer reporting of mechanism evidence and threshold indicators. ~~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 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.

Financial support

This study was financially supported by the National Natural Science Foundation of China (Grant Nos. U2442201 and 52409031).~~U2442201) and the National Natural Science Foundation of China (52409031).~~

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.

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.

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.

Chittolina, M., da Rocha, H. R., Domingues, L. M., and de Araújo Lobo, G.: Hydrological response of a headwater catchment in Southeast Brazil—Threshold patterns of stormflow response, Hydrological Processes, https://doi.org/10.1002/hyp.14879, 2023.

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.

Devito, K. J., O'Sullivan, A. M., Peters, D. L., Hokanson, K. J., Kettridge, N., and Mendoza, C. A.: Runoff Threshold Responses in Continental Boreal Catchments: Nexus of Subhumid Climate, LowRelief, Surficial Geology, and Land Cover, Water Resources Research, 59, https://doi.org/10.1029/2023wr034752, 2023.

Dunne, T. and Black, R. D.: An Experimental Investigation of Runoff Production in Permeable Soils, Water Resources Research, 6, 478–490, https://doi.org/10.1029/WR006i002p00478, 1970.

Farrick, K. K. and Branfireun, B. A.: Soil water storage, rainfall and runoff relationships in a tropical dry forest catchment, Water Resources Research, 50, 9236–9250, https://doi.org/10.1002/2014WR016045, 2014.

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., Hrachowitz, M., Wang-Erlandsson, L., Fenicia, F., Xi, Q., Xia, J., Shao, W., Sun, G., and Savenije, H. H. G.: Root zone in the Earth system, Hydrol. Earth Syst. Sci., 28, 4477–4499, https://doi.org/10.5194/hess-28-4477-2024, 2024.

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.

Jencso, K. and McGlynn, B.: Hierarchical controls on runoff generation: Topographically driven hydrologic connectivity, geology, and vegetation, https://doi.org/10.1029/2011WR010666, 2011.

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.

Kim, H. J.: Hydrologic contributions of subsurface flow during snowmelt and rainfall in a forest catchment, coastal British Columbia, University of British Columbia, https://doi.org/10.14288/1.0090117, 2009.

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.

M. Srinivasan, W. Gburek, and J. Hamlett: Dynamics of stormflow generation—A hillslope-scale field study in east-central Pennsylvania, USA, Hydrological Processes, https://doi.org/10.1002/HYP.311, 2002.

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

McDonnell, J. J., Spence, C., Karran, D. J., Van Meerveld, H. J. (Ilja), and Harman, C. J.: Fill-and-Spill: A Process Description of Runoff Generation at the Scale of the Beholder, Water Resources Research, 57, e2020WR027514, https://doi.org/10.1029/2020WR027514, 2021.

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.

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., Gnann, S. J., and Araki, R.: Large Scale Evaluation of Relationships Between Hydrologic Signatures and Processes, Water Resources Research, 58, e2021WR031751, https://doi.org/10.1029/2021WR031751, 2022.

Meerveld, H. J. and McDonnell, J.: Analysis of subsurface stormflow from 147 storms at the 20 m long trench in the Panola Mountain Research Watershed, 2017.

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.

de Moraes, J. M., Schuler, A. E., Dunne, T., Figueiredo, R. de O., and Victoria, R. L.: Water storage and runoff processes in plinthic soils under forest and pasture in eastern Amazonia, Hydrological Processes, 20, 2509–2526, https://doi.org/10.1002/hyp.6213, 2006.

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.: Exploring Hydrological Connections: A Threshold and Complex Network Based Approach , , https://doi.org/10.5194/egusphere-egu21-7526, 2021.

Oswald, C. J., Richardson, M. C., and Branfireun, B. A.: Water storage dynamics and runoff response of a boreal Shield headwater catchment, Hydrological Processes, 25, 3042–3060, https://doi.org/10.1002/hyp.8036, 2011.

Penna, D.: Controls on runoff processes in forested catchments worldwide, Nat Water, 4, 102–114, https://doi.org/10.1038/s44221-025-00547-z, 2026.

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.

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.

Saffarpour, S.: Interactive comment on "Multiple runoff processes and multiple thresholds control agricultural runoff generation," 2016.

Scaife, C. I. and Band, L. E.: Nonstationarity in threshold response of stormflow in southern A ppalachian headwater catchments, Water Resources Research, 53, 6579–6596, https://doi.org/10.1002/2017WR020376, 2017.

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.

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%3C369::AID-HYP943%3E3.0.CO;2-P, 2000.

Spence, C.: A Paradigm Shift in Hydrology: Storage Thresholds Across Scales Influe nce Catchment Runoff Generation, Geography Compass, 4, 819–833, https://doi.org/10.1111/j.1749-8198.2010.00341.x, 2010.

Spence, C. and Woo, M.: Hydrology of subarctic Canadian shield: soil-filled valleys, Journal of Hydrology, 279, 151–166, https://doi.org/10.1016/S0022-1694(03)00175-6, 2003.

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, 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, 2022.

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.

Zehe, E. and Sivapalan, M.: Threshold behaviour in hydrological systems as (human) geo-ecosystems: manifestations, controls, implications, Hydrol. Earth Syst. Sci., 13, 1273–1297, https://doi.org/10.5194/hess-13-1273-2009, 2009.

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.

Zhang, J., Liu, J., Han, X., Shen, X., Liang, Z., and Wang, S.: Variable storage behavior controlled by rainfall intensity and profile structure upon saturation excess overland flow generation, Journal of Hydrology, 610, 127860, https://doi.org/10.1016/j.jhydrol.2022.127860, 2022.

Zhang, Y., Guo, L., Xu, H., Liu, H., Liu, J., Sun, X., Mello, C. R., Boyer, E., and Wang, G.: Quantifying Subsurface Hydrological Connectivity and Its Coupling With Structural Connectivity in Headwater Catchments, Water Resources Research, 62, e2025WR042599, https://doi.org/10.1029/2025WR042599, 2026.

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.

Appendix A.

Table A1. Harmonization and classification rules for runoff generation mechanism classes used in this study.

Class	Terms harmonized under this class	Classification rule
HOF	Hortonian overland flow; infiltration-excess overland flow; infiltration-limited runoff	Used when the source study explicitly interpreted surface runoff as infiltration-excess/Hortonian
SOF	Saturation-excess overland flow; return flow; saturated-area runoff	Used when the source study interpreted surface runoff as saturation-excess or saturated-area expansion
SSF	Subsurface stormflow; lateral subsurface flow; interflow; macropore/pipe flow	Used when lateral event-scale subsurface flow was reported
GWF	Shallow groundwater flow; weathered/fractured bedrock groundwater contribution	Used only for event-scale shallow groundwater contribution to stormflow
Mixed	HOF–SOF, SOF–SSF, SSF–GWF, etc.	Used when co-dominance or switching was explicitly reported

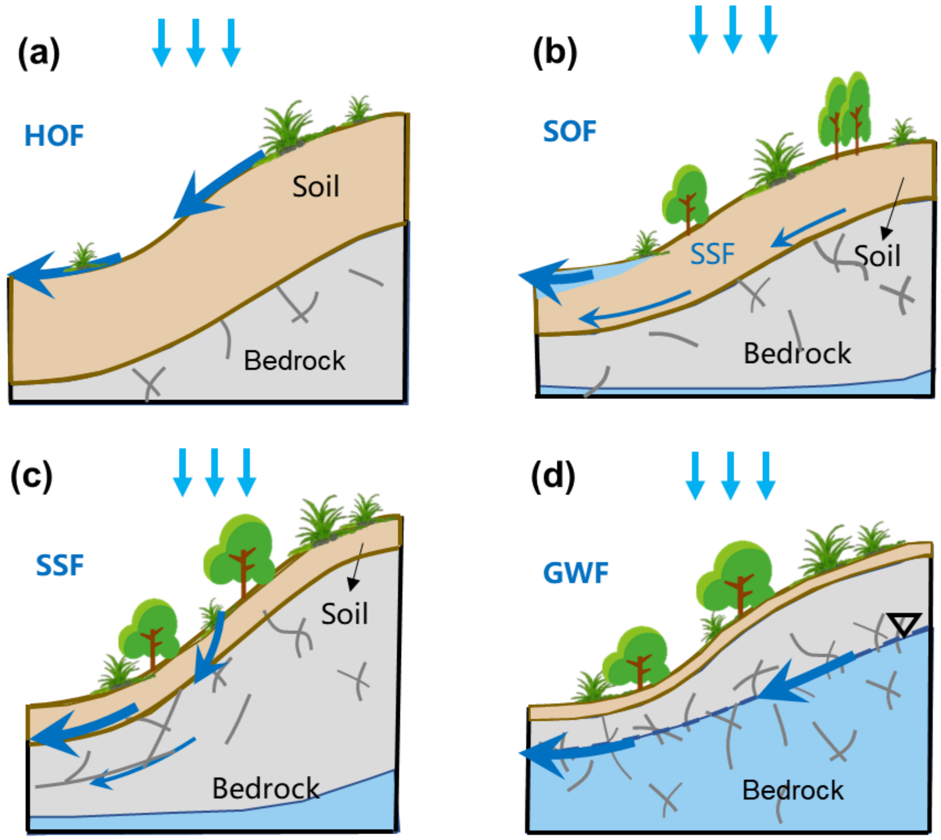


Figure A1. Conceptual schematic of runoff generation mechanism classes used in this review. HOF denotes infiltration-excess surface runoff; SOF denotes runoff from saturated or near-saturated source areas; SSF denotes event-scale lateral subsurface stormflow through soil, regolith, preferential pathways, or restrictive interfaces; and GWF denotes event-scale shallow groundwater response within weathered bedrock or fractured regolith contributing to stormflow. The schematic is intended to clarify classification terminology and does not imply that all catchments contain all pathways or that these mechanisms are mutually exclusive.

Table ~~A1~~A2. 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	Storage~~SWC & GWL~~	SOF
Saalach	Austria	-	AMC	SSF
USR	USA	ASI & P	Storage~~SWC & GWL~~	SSF & GWF
XEW	China	ASI & P	Storage~~SWC & GWL~~	GWF
Plynlimon	United Kingdom	-	Storage	SOF
LGC	New Zealand	ASI & P	SWC~~ASW~~	SOF
Bongsunsa	Korea	ASI & P	SWC~~ASW~~	SSF
MSRB	Japan	API	AMC	SSF
RRC	USA	-	AMC	SSF
FSSF	Brazil	-	SWC~~ASW~~	SOF & SSF
Yingtan	China	ASI & P	SWC~~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
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	Storage~~SWC & GWL~~	SOF & SSF
Pinios	Greece	P	-	SOF
HM	Luxembourg	-	-	SOF & SSF
KOE	Luxembourg	-	AMC	SOF & GWF
L1	Japan	ASI & P	~~ASW~~SWC	SSF
JPG	China	ASI & P	SWC~~ASW~~	SSF
SEO	Germany	-	-	SSF
SIR	Chile	P	SWC	SOF
Maimai	New Zealand	P	-	SSF
Toro	USA	-	-	HOF & SOF
Utuado	USA	-	SWC~~ASW~~	SSF
Uhlirska	Czech Republic	-	AMC	SSF
GCC	France	SWC	SWC~~ASW~~	SSF
C3	USA	-	-	SSF
CB	USA	-	-	SSF
R5	USA	-	-	HOF & SOF
TW	Australia	-	SWC~~AMC~~	SOF
GCEW	USA	ASI & P	SWC~~ASW~~	SSF

PC1-08	Canada	GWL	GWL	SOF & SSF
Marcell	USA	-	SWC~~ASW~~	SOF & SSF
WS10	USA	P	AMC	SSF
PLB	Canada	-	AMC	SSF
PEC	United Kingdom	-	SWC~~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	SWC~~ASW~~	SSF
Ponderosa	USA	SWC	SWC~~ASW~~	SSF
Hermine	Canada	Storage	Storage	SSF
RBF	Australia	ASI & P	SWC~~ASW~~	SOF & SSF
Odersprung	Germany	GWL	GWL	SOF
CHL	USA	ASI & P	SWC~~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	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	SWC~~ASW~~	SOF
Mösern	Austria	SWC	SWC~~ASW~~	SOF
Yanglou	China	P	AMC	GWF
MWYW	USA	Pi	-	HOF
WGEW	USA	Pi	-	HOF

Mulian	China	ASI & P	SWC~~ASW~~	SSF
Corbeira	Spain	P	AMC	SSF
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	SWC~~ASW~~	SSF
Alptal	Switzerland	-	GWL	SOF
HMD	UK	SWC	SWC~~ASW~~	SSF
Ina	Japan	P	AMC	SSF & GWF
MNC	Japan	ASI & P	SWC~~ASW~~	SSF
CVC	Spain	SWC	SWC	SOF
AEB	Brazil	P	-	HOF
VSC	Argentina	P	AMC	SSF
Jiufeng	China	SWC	SWC~~ASW~~	HOF
Matalom	Philippines	P	SWC~~ASW~~	SOF & SSF
Ressi	Italy	ASI & P	SWC~~ASW~~	SSF
DFP	USA	SWC	SWC~~ASW~~	SOF
LZW	Mexico	SWC	SWC~~ASW~~	SSF
CRC	Spain	P	AMC	SOF
Mahurangi	New Zealand	P	SWC~~ASW~~	SOF & SSF
BCC	Italy	ASI & P	SWC~~ASW~~	SSF & GWF
WAWC	Austria	P	Storage	SOF & SSF
Weierbach	Luxembourg	Storage	Storage	GWF
Nanxiaohe	China	ASI & P	SWC~~ASW~~	HOF
LXR	China	ASI & P	SWC~~ASW~~	SSF
HOEW	Japan	API	AMC	SSF

SDSC	China	ASI & P	SWC~~ASW~~	SSF
GRC	USA	Storage	Storage	SSF
SH	USA	SWC	Storage	SOF & SSF
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	SWC~~ASW~~	SSF
PEW	Spain	SWC	SWC~~ASW~~	SOF & SSF
CERB	China	P	SWC~~ASW~~	SSF
WS3	USA	ASI & P	SWC~~SWC~~	SSF
KREW	USA	ASI & P	SWC~~ASW~~	SSF
PMRW	USA	P	SWC~~ASW~~	SSF
DCD	USA	ASI & P	AMC	SSF
UGCC	Canada	GWL	SWC	SSF
Quinuas	Ecuador	SWC	-	SSF
Ciciriello	Italy	-	SWC~~ASW~~	GWF
OCR	USA	SWC	-	SSF
UP1	Canada	Storage	Storage	SOF
HBEF	USA	-	SWC~~ASW~~	SOF & SSF

Note: antecedent moisture condition (AMC), soil water content (SWC), groundwater level (GWL), and integrated storage state

Table A3. Synonym normalization of hydrological state descriptors and threshold indicators used in Fig. 3.

Category in Fig. 2	**Original terms reported in literature**	**Standardized descriptor used in this study**
	antecedent wetness, antecedent moisture condition, wet/dry condition, antecedent precipitation index, antecedent baseflow	Antecedent moisture condition
Hydrological state domain	antecedent soil moisture, antecedent soil water content, initial soil moisture, initial soil water content, soil moisture, soil water content, volumetric water content	Soil water content
	groundwater level, groundwater table, water-table level, water-table depth	Groundwater level
	catchment storage state, storage deficit, soil-water storage, catchment water storage, coupled soil moisture and groundwater level	Integrated storage state
	event precipitation, event rainfall, storm rainfall, total rainfall, rainfall amount, cumulative rainfall	P
	rainfall intensity, storm intensity, maximum rainfall intensity, peak rainfall intensity, precipitation intensity	Pi
	antecedent precipitation index, antecedent rainfall index, API	API
Threshold indicator	soil water content, soil moisture, volumetric water content, antecedent soil moisture threshold	SWC
	groundwater level, groundwater table, water-table depth, groundwater-level threshold	GWL
	catchment storage, storage deficit, storage threshold	Storage
	rainfall plus antecedent wetness, rainfall plus soil moisture, rainfall plus API, rainfall plus storage, rainfall plus groundwater level, combined rainfall–state index	Composite indicator

Table ~~A2~~A4. 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