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

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Key Points:

- Reported runoff thresholds are more often characterized by antecedent or within-event catchment-state indicators than by rainfall metrics alone.
- 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 threshold behavior, and connectivity development.

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 settings. 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.

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

1. Introduction

Storm runoff generation often exhibits nonlinearity or threshold-like behavior, where small changes in rainfall or antecedent wetness can trigger disproportionate increases in runoff. Numerous event-based studies show that runoff outcomes vary with catchment wetness, storage conditions, and activation of surface, subsurface, or groundwater pathways (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.

Connectivity- and storage-based frameworks have therefore shifted attention from fixed rainfall thresholds to state-dependent activation of flow paths. Fill-and-spill concepts emphasize the episodic filling and coupling of surface, subsurface, or depressional storage (McDonnell et al., 2021; Spence and Woo, 2003; Tromp-van Meerveld and McDonnell, 2006b), while hydrologic connectivity theory frames runoff response as an 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 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 (Deng et al., 2024; Kampf et al., 2018; Ross et al., 2021; Sidle et al., 2000; Scaife et al., 2020), 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.

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.

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.

Specifically, we address three questions:

1. Which rainfall-based, state-based, or composite indicators are used in the literature to identify threshold-like storm-runoff responses?

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?

3. Which recurring soil–geology–hydrogeology settings are associated with different reported runoff mechanisms and their wetness-dependent activation?

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.

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 mechanisms.

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.

Studies were retained if they: (i) provided well-documented storm-event observations, such as rainfall and runoff time series, hydrograph or hysteresis analyses, soil moisture or groundwater dynamics, tracers or isotopes, or similar process evidence), and (ii) explicitly interpretation of nonlinear or threshold-like runoff behavior 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.

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.

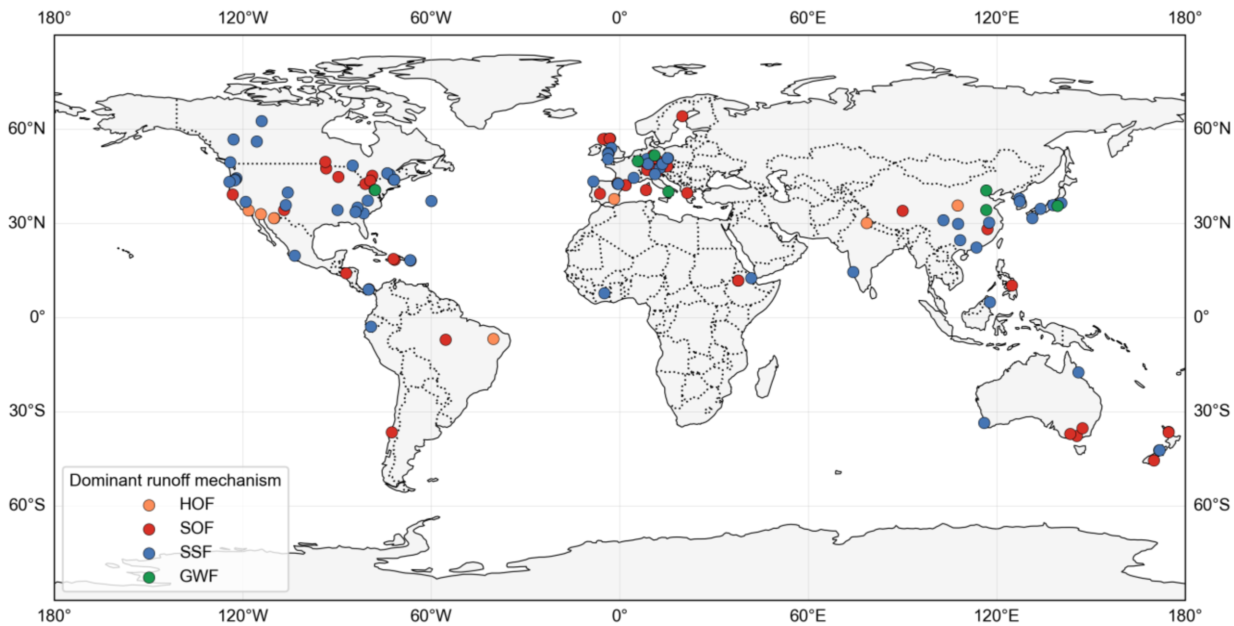

Figure 1. Global distribution of study catchments categorized by dominant runoff generation mechanisms. Colored symbols indicate the dominant or combined runoff generation mechanisms reported for each catchment, including HOF, SOF, SSF, GWF.

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.

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.

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 3.4. 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, based on climate descriptions, 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. 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 co-occurrence network

To examine recurring associations between dominant runoff generation mechanisms and subsurface characteristics, we conducted a soil–geology ‑ hydrogeology keyword co-occurrence analysis. This analysis identifies combinations of soil, geological, and hydrogeological 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. To ensure consistency across studies, extracted descriptors were standardized using a synonym normalization table (Table 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. 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, 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

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.

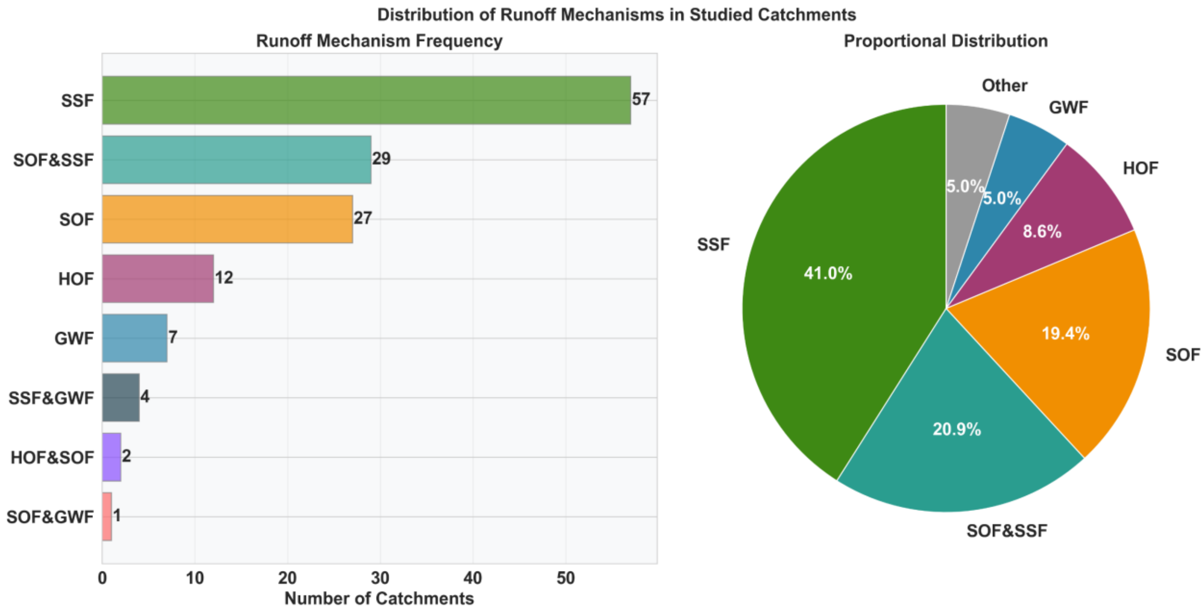

Figure 2. Frequency and proportional contribution of reported dominant runoff generation mechanisms in the reviewed catchments. The left panel shows the number of catchments classified under each dominant mechanism or mechanism combination, based on the primary interpretation in the original studies.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

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 moisture condition, soil water content, groundwater level, and integrated storage state. 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.

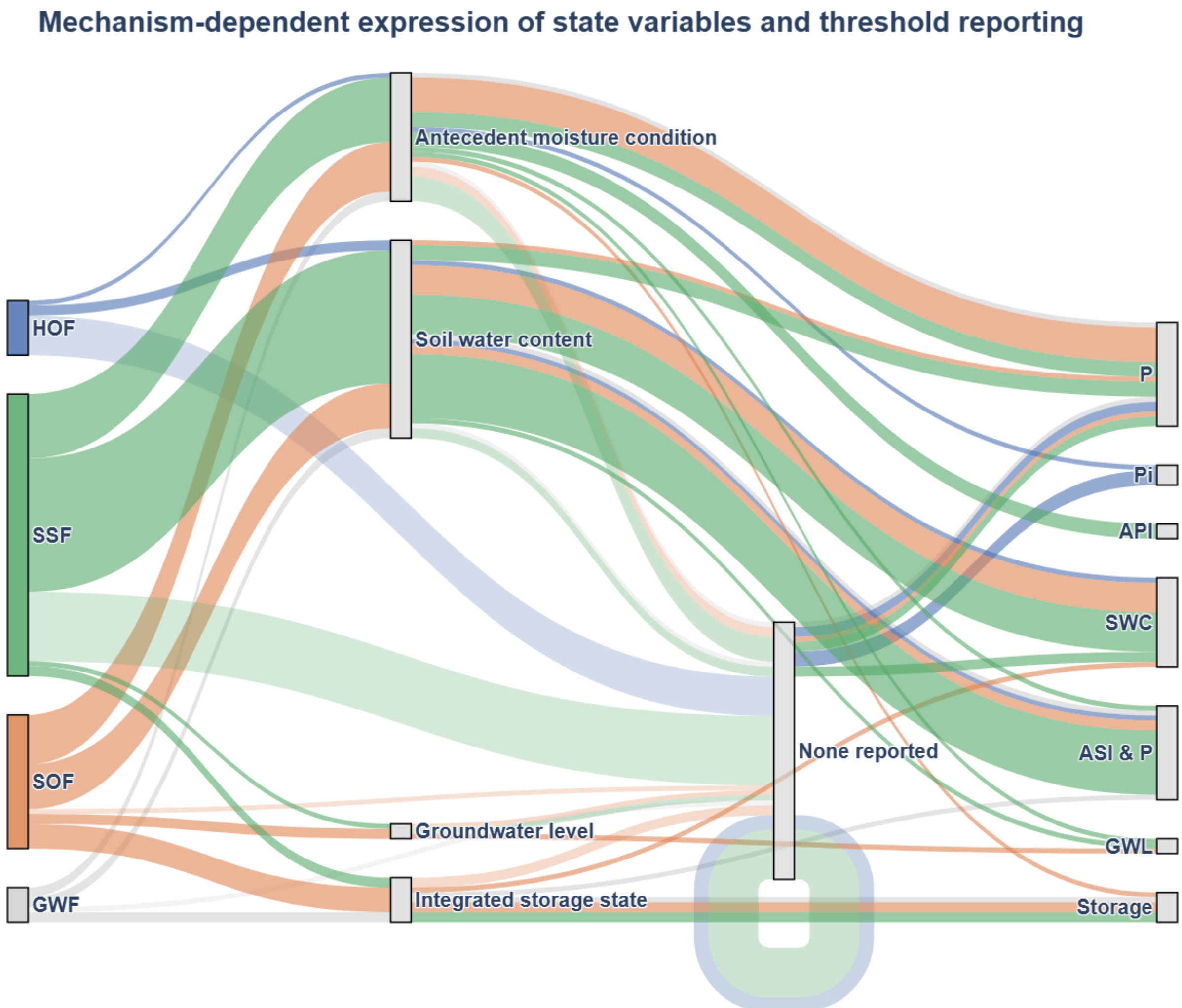

Figure 3. Sankey diagram summarizing reported trigger–state indicators used to identify nonlinear runoff threshold behavior across dominant runoff generation mechanisms. Rectangular node height is proportional to the number of catchments. P, event rainfall amount; Pi, rainfall intensity; API, antecedent precipitation index; SWC, soil water content or soil moisture; GWL, groundwater level; Storage, catchment storage. Nodes on the left represent dominant runoff mechanisms, middle nodes represent hydrological state variables, and 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 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.

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.

3.2 Distribution of reported dominant mechanisms across aridity and vegetation classes

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 classes (humid, semi-humid, semi-arid, and arid) and across major vegetation types. Single and combined mechanisms are shown separately.

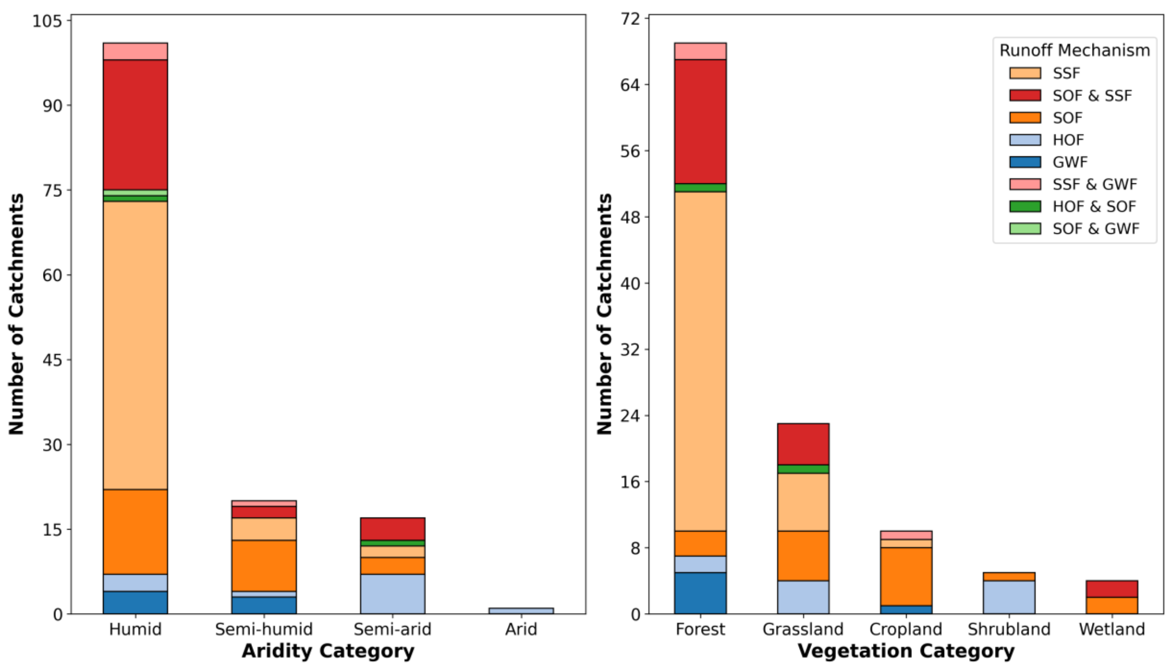

Figure 4. Distribution of dominant runoff generation mechanisms across aridity and vegetation categories. Bars show the number of catchments in each aridity or vegetation class, with each catchment counted once.

Within the reviewed dataset (Fig. 4a), humid catchments constitute the largest subset and therefore include the widest range of reported runoff generation mechanisms. Among these humid catchments, SSF is the most frequently reported mechanism, followed by SOF and combined SOF–SSF mechanisms. Groundwater-related mechanisms (GWF and SSF–GWF) are represented mainly by humid catchments in this dataset. Semi-humid catchments are fewer in number and most commonly report SOF, with additional cases of SSF and GWF. In the semi-arid subset, the total number of catchments is smaller; SSF and SOF are still represented, while HOF accounts for a larger proportion of the reviewed semi-arid cases. The single arid catchment included in the dataset was classified as HOF-dominated.

Vegetation-related patterns should be interpreted even more cautiously because the reviewed catchments are strongly uneven across land-cover classes (Fig. 4b). Forested catchments are overrepresented in the dataset and include 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.

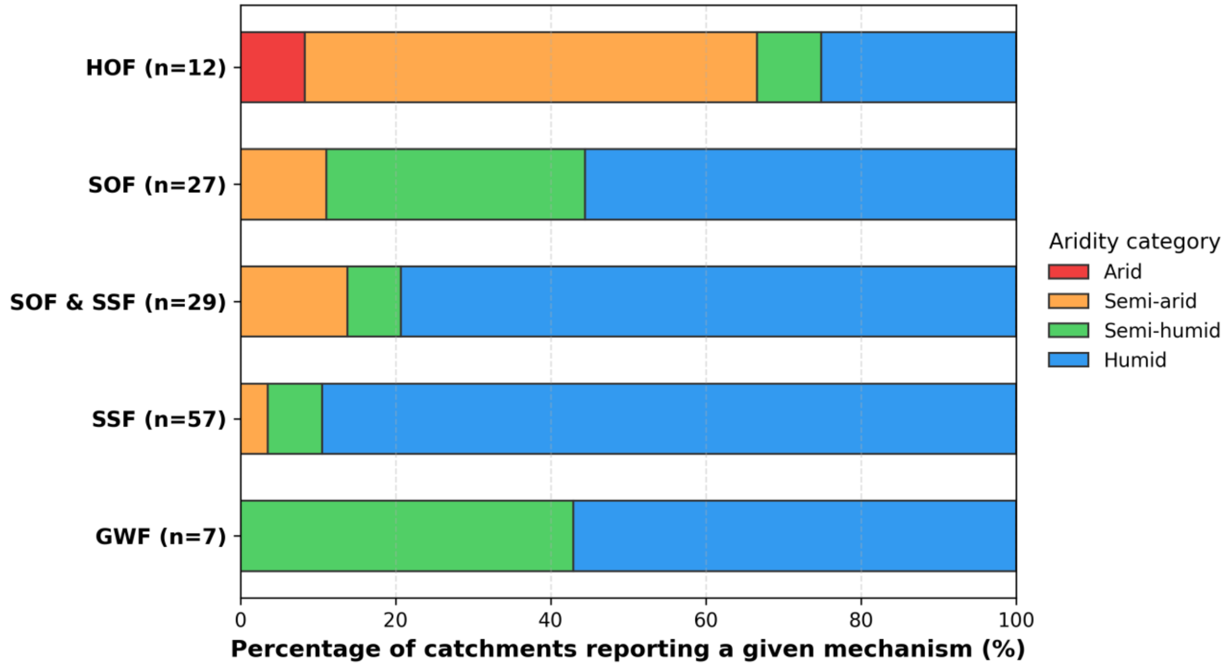

Figure 5. Distribution of aridity for the catchments for which each dominant runoff generation mechanism was reported. Percentages are calculated relative to the total number of catchments reporting each mechanism, such that each bar sums to 100%.

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.

3.3 Reported event-scale transitions in dominant runoff generation mechanisms within catchments

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. 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.

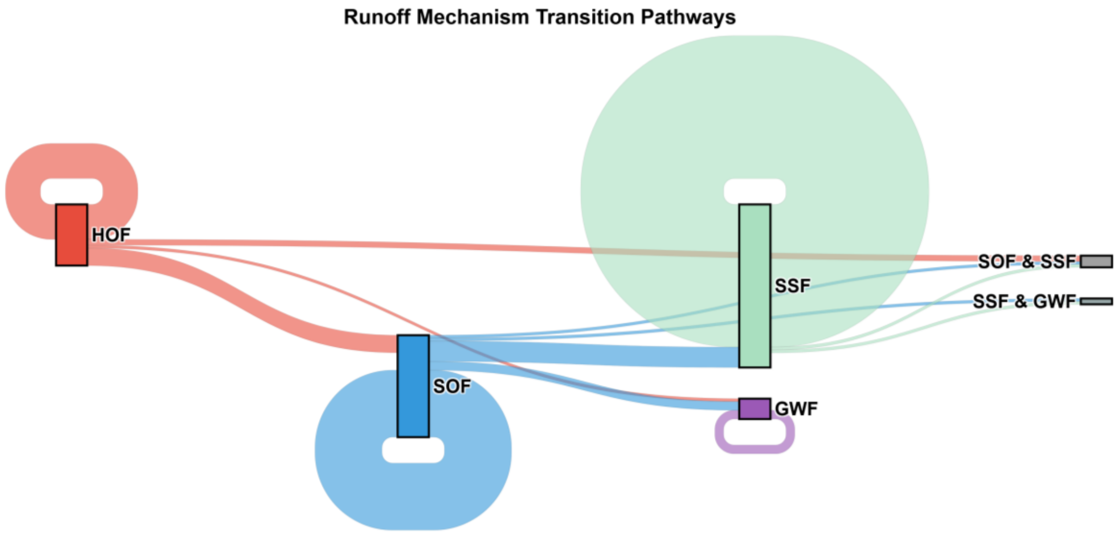

Figure 6. Sankey diagram illustrating reported runoff-mechanism transition pathways under increasing catchment wetness. The diagram includes only catchments with explicitly reported wetness-dependent mechanism shifts or persistence. Rectangular node height is proportional to the number of catchments 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.

Catchments initially dominated by HOF typically shifted toward SOF (29), combined SOF–SSF responses (10%), and less frequently, groundwater-dominated flow (5%). Catchments initially dominated by SOF shifted toward SSF (20%), GWF (9%), and mixed SOF–SSF (3%) and SSF–GWF responses (3%). Transitions originating from SSF were less frequently reported, but include shifts toward SOF–SSF (4%) and SSF–GWF (2%).

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.

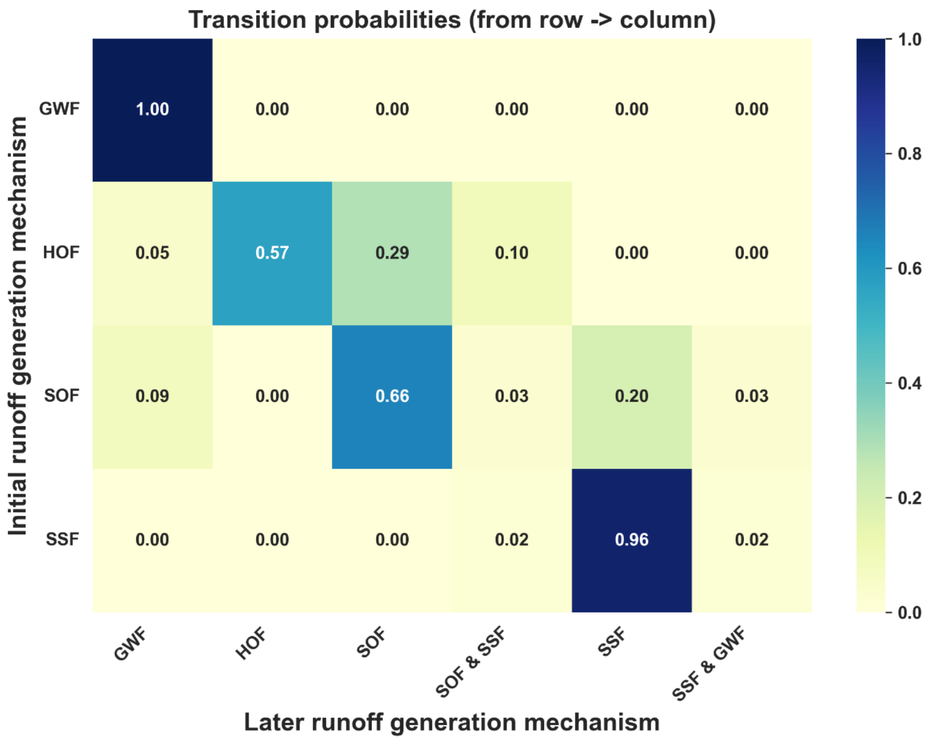

Figure 7. Conditional transition probabilities between dominant runoff generation mechanisms under increasing wetness. Values represent the proportion of catchments with a given initial mechanism (rows) that transitioned to each subsequent mechanism (columns). Transition probabilities were calculated 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. 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 ($p < 0.05$).

3.4 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. 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.

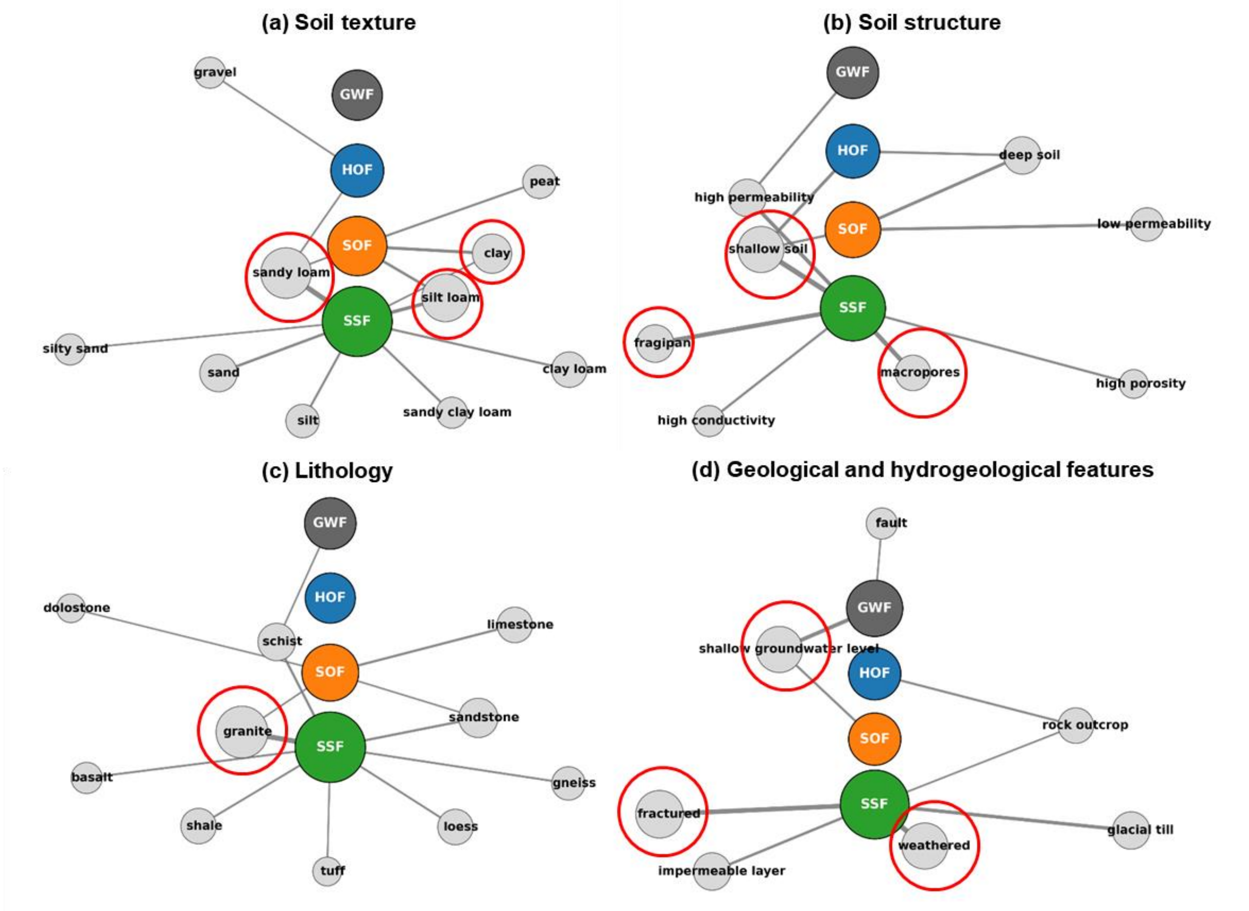

Figure 8. Soil–geology ‑ hydrogeology fingerprints of dominant runoff generation mechanisms. Panels show co-occurrence relationships with (a) soil texture, (b) soil structural properties, (c) lithology, and (d) geological and hydrogeological features. Colored nodes represent dominant runoff mechanisms—HOF, SOF, SSF, and GWF—while gray nodes represent soil or geological descriptors 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).

There are strong co-occurrence links between SOF and clay and loam textures, deep soils, and low permeability. It is also frequently associated with 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 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. 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.

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 (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.

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).

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).

4.2 Why do thresholds differ across mechanisms and catchments?

Differences in reported 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). 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.

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.

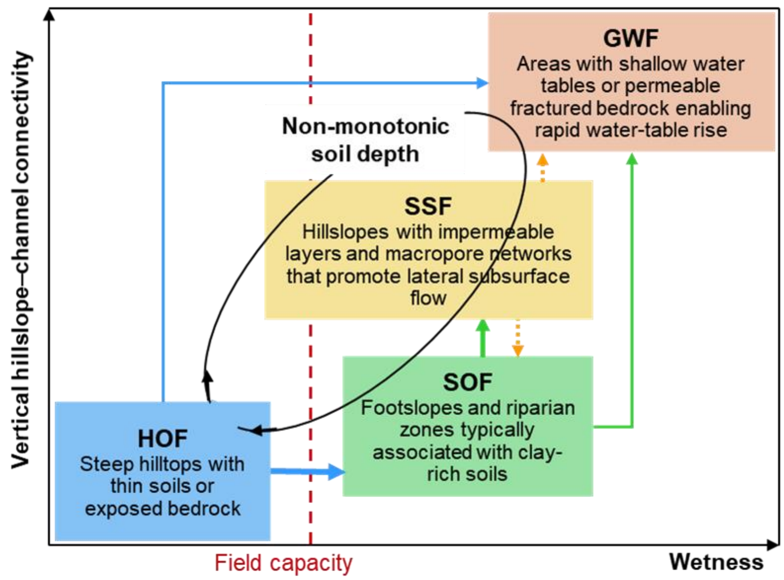

Figure 9. Conceptual framework of event-scale runoff mechanism transitions across gradients of wetness and vertical flow-path integration. The x-axis represents increasing antecedent and within-event wetness or storage state. The y-axis represents the conceptual vertical integration or depth extent of 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.

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). 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.

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.

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.

Data availability

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

Author contribution

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

Competing interests

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

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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

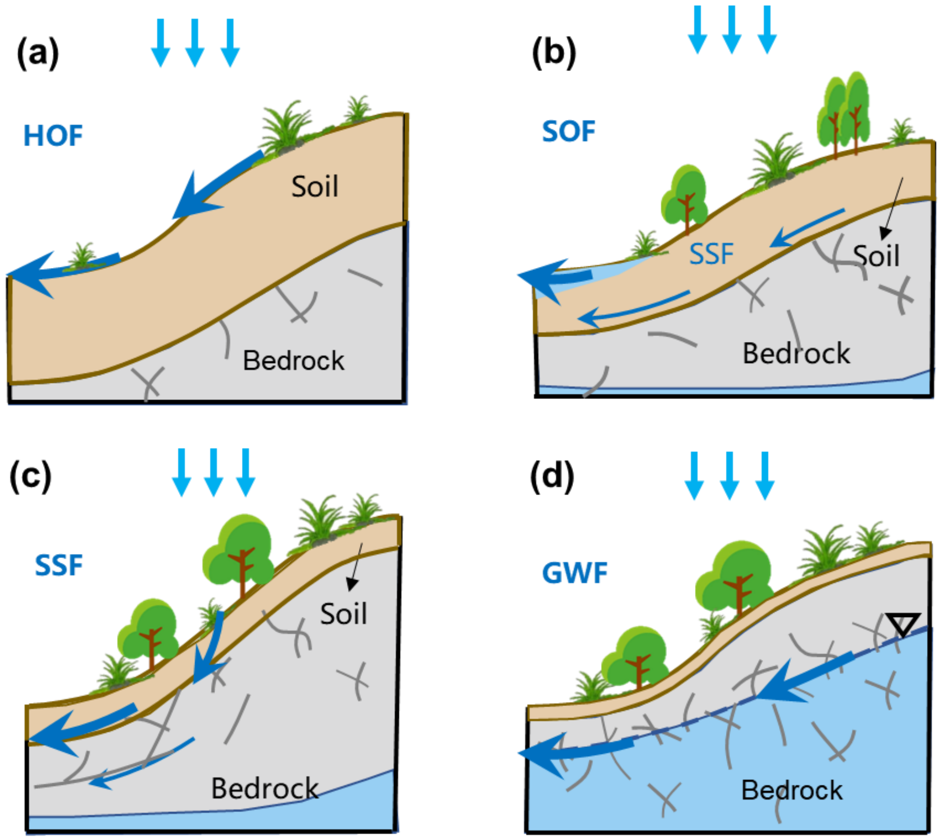

Figure A1. Conceptual schematic of runoff generation mechanism classes used in this review. HOF denotes infiltration-excess surface runoff; SOF denotes runoff from saturated or near-saturated source areas; SSF denotes event-scale lateral subsurface stormflow through soil, regolith, preferential pathways, 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 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	SOF
Saalach	Austria	-	AMC	SSF
USR	USA	ASI & P	Storage	SSF & GWF
XEW	China	ASI & P	Storage	GWF
Plynlimon	United Kingdom	-	Storage	SOF
LGC	New Zealand	ASI & P	SWC	SOF
Bongsunsa	Korea	ASI & P	SWC	SSF
MSRB	Japan	API	AMC	SSF
RRC	USA	-	AMC	SSF
FSSF	Brazil	-	SWC	SOF & SSF
Yingtan	China	ASI & P	SWC	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	SOF & SSF
Pinios	Greece	P	-	SOF
HM	Luxembourg	-	-	SOF & SSF
KOE	Luxembourg	-	AMC	SOF & GWF
L1	Japan	ASI & P	SWC	SSF
JPG	China	ASI & P	SWC	SSF
SEO	Germany	-	-	SSF
SIR	Chile	P	SWC	SOF
Maimai	New Zealand	P	-	SSF
Toro	USA	-	-	HOF & SOF
Utuado	USA	-	SWC	SSF
Uhlirska	Czech Republic	-	AMC	SSF
GCC	France	SWC	SWC	SSF
C3	USA	-	-	SSF
CB	USA	-	-	SSF
R5	USA	-	-	HOF & SOF
TW	Australia	-	SWC	SOF
GCEW	USA	ASI & P	SWC	SSF
PC1-08	Canada	GWL	GWL	SOF & SSF
Marcell	USA	-	SWC	SOF & SSF

WS10	USA	P	AMC	SSF
PLB	Canada	-	AMC	SSF
PEC	United Kingdom	-	SWC	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	SSF
Ponderosa	USA	SWC	SWC	SSF
Hermine	Canada	Storage	Storage	SSF
RBF	Australia	ASI & P	SWC	SOF & SSF
Odersprung	Germany	GWL	GWL	SOF
CHL	USA	ASI & P	SWC	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	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	SOF
Mösern	Austria	SWC	SWC	SOF
Yanglou	China	P	AMC	GWF
MWYW	USA	Pi	-	HOF
WGEW	USA	Pi	-	HOF
Mulian	China	ASI & P	SWC	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	SSF
Alptal	Switzerland	-	GWL	SOF
HMD	UK	SWC	SWC	SSF
Ina	Japan	P	AMC	SSF & GWF
MNC	Japan	ASI & P	SWC	SSF
CVC	Spain	SWC	SWC	SOF
AEB	Brazil	P	-	HOF
VSC	Argentina	P	AMC	SSF
Jiufeng	China	SWC	SWC	HOF
Matalom	Philippines	P	SWC	SOF & SSF
Ressi	Italy	ASI & P	SWC	SSF
DFP	USA	SWC	SWC	SOF
LZW	Mexico	SWC	SWC	SSF
CRC	Spain	P	AMC	SOF
Mahurangi	New Zealand	P	SWC	SOF & SSF
BCC	Italy	ASI & P	SWC	SSF & GWF
WAWC	Austria	P	Storage	SOF & SSF
Weierbach	Luxembourg	Storage	Storage	GWF
Nanxiaohe	China	ASI & P	SWC	HOF
LXR	China	ASI & P	SWC	SSF
HOEW	Japan	API	AMC	SSF
SDSC	China	ASI & P	SWC	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	SSF
PEW	Spain	SWC	SWC	SOF & SSF
CERB	China	P	SWC	SSF
WS3	USA	ASI & P	SWC	SSF
KREW	USA	ASI & P	SWC	SSF
PMRW	USA	P	SWC	SSF
DCD	USA	ASI & P	AMC	SSF
UGCC	Canada	GWL	SWC	SSF
Quinuas	Ecuador	SWC	-	SSF
Ciciriello	Italy	-	SWC	GWF
OCR	USA	SWC	-	SSF
UP1	Canada	Storage	Storage	SOF
HBEF	USA	-	SWC	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**
Hydrological state domain	antecedent wetness, antecedent moisture condition, wet/dry condition, antecedent precipitation index, antecedent baseflow	Antecedent moisture condition
	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
Threshold indicator	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
	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 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