



17 **Abstract**

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

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



43 1. Introduction

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

52 Subsequent advances shifted focus from fixed rainfall thresholds to state-dependent
53 activation of hydrologic connectivity. Fill-and-spill concepts emphasized the episodic activation
54 and coupling of subsurface and depressional storage once critical wetness thresholds are
55 exceeded (Green and Crumpton, 2023; Jehn et al., 2021; McDonnell, 2013), while hydrologic
56 connectivity theory framed runoff response as an emergent outcome of progressively coupled
57 hillslopes, soils, groundwater, and channels (Blume and Meerveld, 2015; Fu et al., 2013;
58 McDonnell, 2013). Connectivity- and storage-based frameworks further demonstrated that
59 threshold-like runoff behavior emerges when incremental rainfall leads to disproportionate
60 increases in internal hydrologic connectivity and flow transmission (Ares et al., 2020; von
61 Freyberg et al., 2014; McGuire and McDonnell, 2010; Wilson et al., 2017; Zimmermann et al.,
62 2014). Despite these advances, the question remains: why do similar storms generate
63 fundamentally different runoff responses across events and catchments?

64 Despite conceptual progress, challenges remain in synthesizing storm runoff nonlinearity
65 across catchments. Threshold behavior—marked by abrupt runoff increases or shifts in dominant
66 flow pathways—has been robustly documented for infiltration-excess overland flow (Deng et al.,
67 2024; Kampf et al., 2018; Lana-Renault et al., 2013; Ross et al., 2021)), saturation-excess
68 overland flow (Mentzafou et al., 2023; Ross et al., 2021; Steenhuis et al., 2013; Wang et al.,
69 2022b), subsurface stormflow (Kirchner, 2024; Lee and Kim, 2020; Sidle et al., 2000; Wang et al.,
70 2022a), and shallow groundwater-dominated responses (Cui et al., 2024; Gao et al., 2024;
71 Graeff et al., 2009; Scaife et al., 2020). However, while threshold responses are well recognized,
72 a comprehensive cross-mechanism synthesis explaining how differences in storage states,



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

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

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



103

104 Specifically, we address the following questions:

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

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

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

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

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

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

127 **2. Data and Methods**

128 **2.1 Literature synthesis and catchment database**

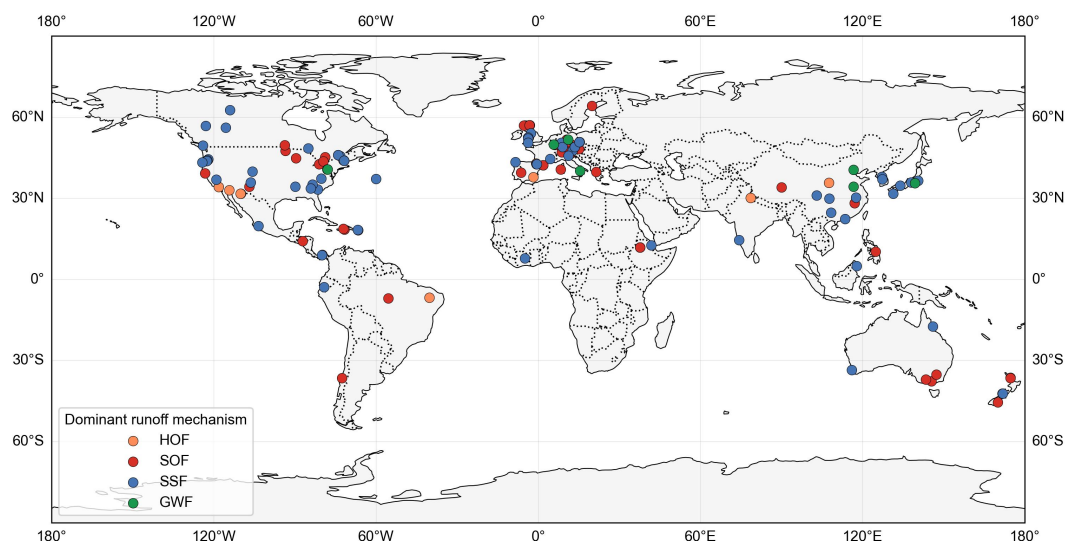
129 To systematically investigate nonlinear and threshold-driven runoff generation under storm
130 conditions, we conducted a comprehensive synthesis of the international literature on rainfall–
131 runoff nonlinearity, abrupt hydrological response shifts, and runoff threshold behavior. The



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

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

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



153

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

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

164 For each catchment, we extracted information on:

- 165 (i) Aridity category and vegetation type;
- 166 (ii) Soil properties, including depth, texture, and permeability;
- 167 (iii) Geological and hydrogeological characteristics; and
- 168 (iv) Reported dominant runoff generation mechanisms, along with the state variables and
169 indicators used to identify nonlinear or threshold runoff behavior.

170 **2.2 Classification of runoff generation mechanisms**

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



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

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

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

187 **2.3 Definition of runoff regime shifts and threshold conditions**

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

- 192 (i) a distinct breakpoint in the rainfall–runoff relationship;
- 193 (ii) a disproportionate increase in runoff relative to rainfall input;
- 194 (iii) a documented transition in dominant runoff generation mechanism; or
- 195 (iv) enhanced hydrological connectivity, such as hillslope–channel coupling, activation of
196 soil–bedrock interfaces, or rapid groundwater table rise.

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



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

206 **2.4 Climate and vegetation classification**

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

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

218 **2.5 Soil–geology keyword co-occurrence network**

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

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

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



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

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

246 **3. Results**

247 **3.1 Reported state variables and indicators of runoff threshold behavior**

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

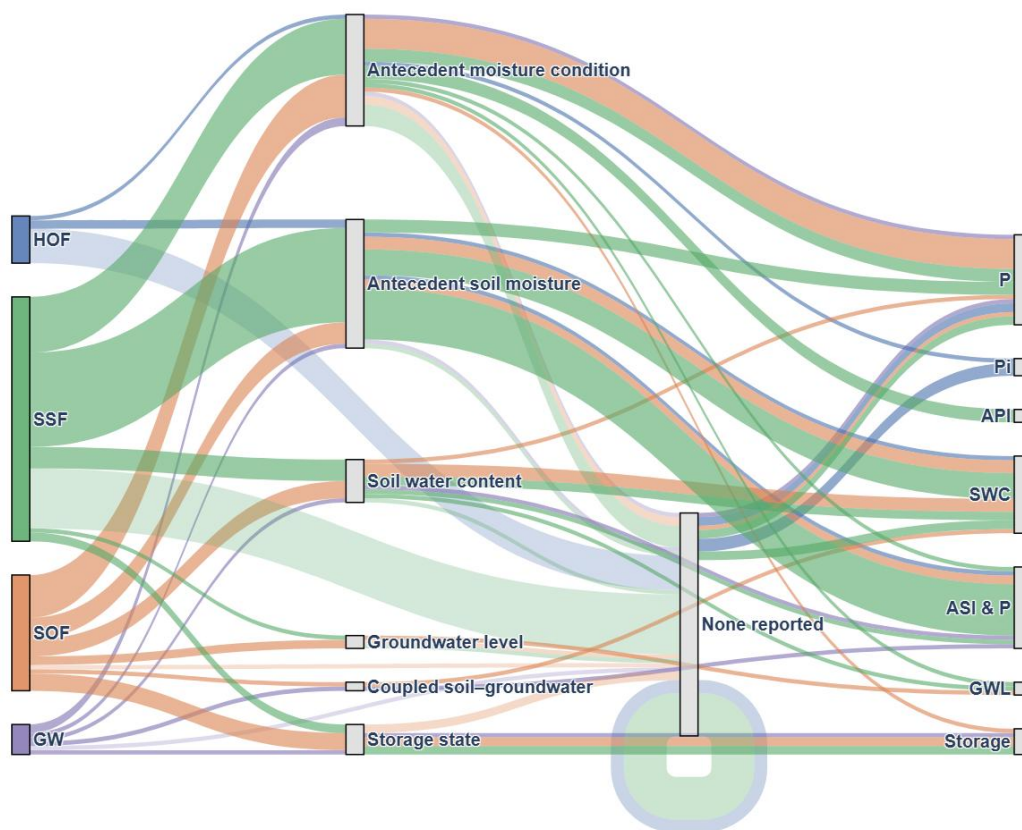
251 The global distribution of the reviewed catchments and their reported dominant runoff
252 generation mechanisms is shown in Fig. 1. To facilitate comparison across mechanisms, Fig. 2
253 synthesizes state variables and threshold indicators for four dominant runoff generation
254 mechanisms—HOF, SOF,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

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



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

Mechanism-dependent expression of state variables and threshold reporting



263

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

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

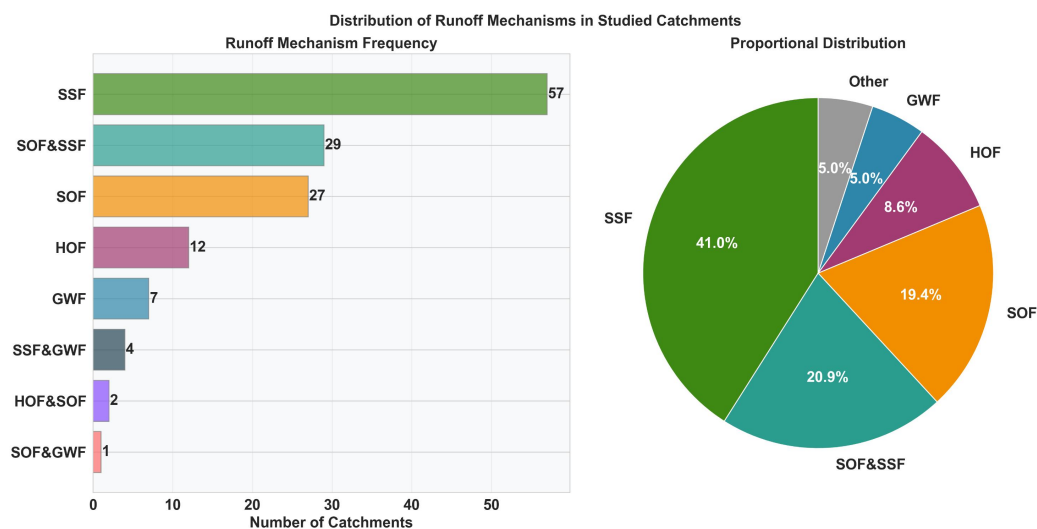


275 quantitative indicator of nonlinear behavior was reported, with threshold behavior identified
276 qualitatively.

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

283 3.2 Frequency and proportional contribution of dominant runoff generation mechanisms

284 Figure 3 summarizes the absolute frequency and relative contribution of dominant runoff
285 generation mechanisms across the reviewed catchments. Panel (a) shows the number of
286 catchments associated with each mechanism, while panel (b) presents their proportional
287 contribution to the dataset. Across all reviewed studies, subsurface-related mechanisms are more
288 frequently reported. SSF is the most common mechanism, accounting for 41.0% of all
289 catchments, followed by combined SOF–SSF mechanisms (20.9%) and SOF alone (19.4%).
290 Together, SSF, SOF, and their combinations represent the majority of reported cases.



291

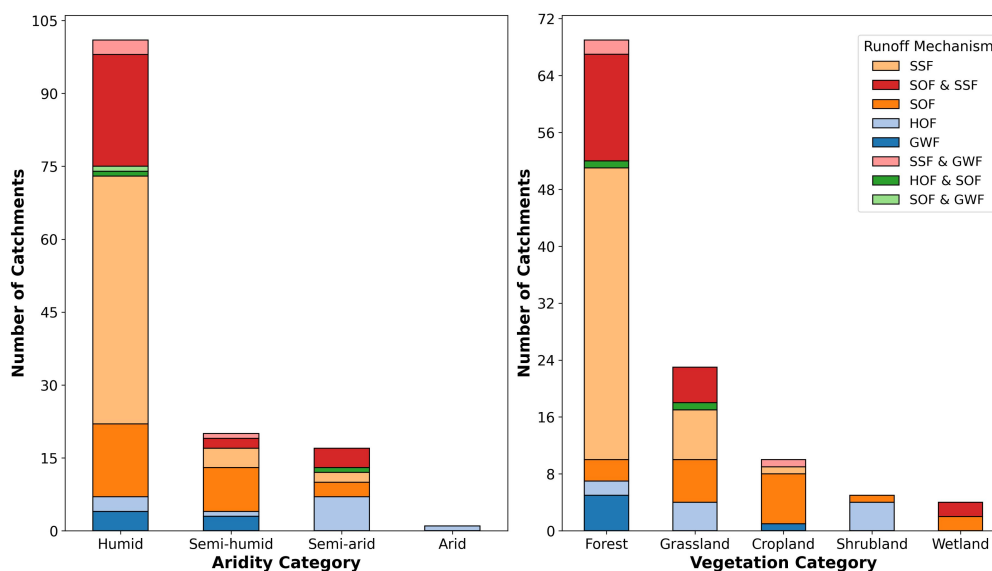


292 **Figure 3.** Frequency and proportional contribution of dominant runoff generation mechanisms
 293 reported in the reviewed catchments. The left panel shows the number of catchments classified
 294 under each dominant runoff mechanism or reported mechanism combination, based on the
 295 primary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

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

299 3.3 Aridity- and vegetation-specific partitioning of dominant runoff generation mechanisms

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



304

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

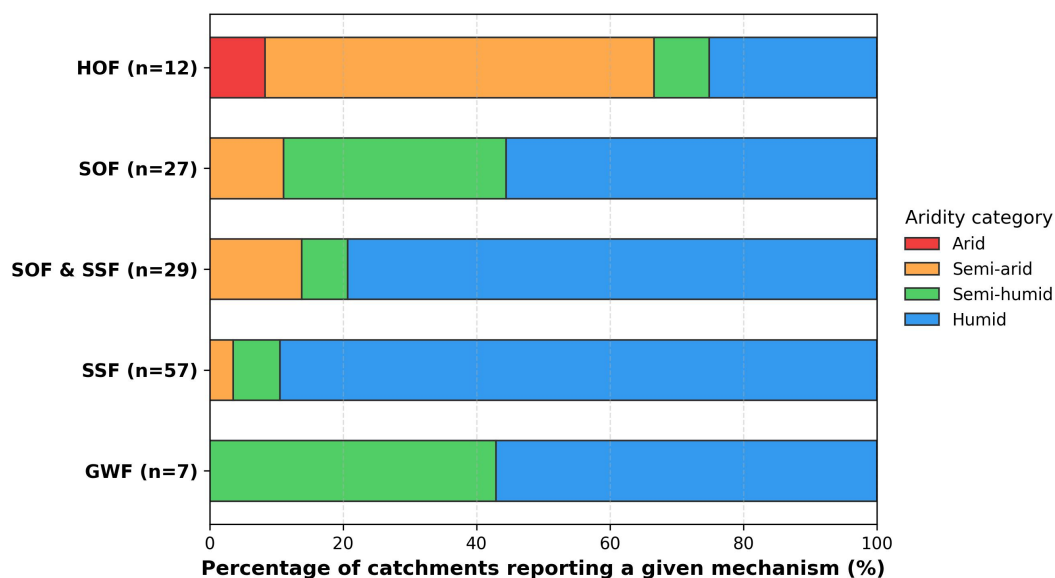
307 Across the aridity gradient (Fig. 4a), humid catchments account for the majority of
 308 observations and exhibit the widest range of reported runoff generation mechanisms. SSF
 309 represents the largest share, followed by SOF and combined SOF–SSF mechanisms.
 310 Groundwater-related mechanisms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



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

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

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



324

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

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

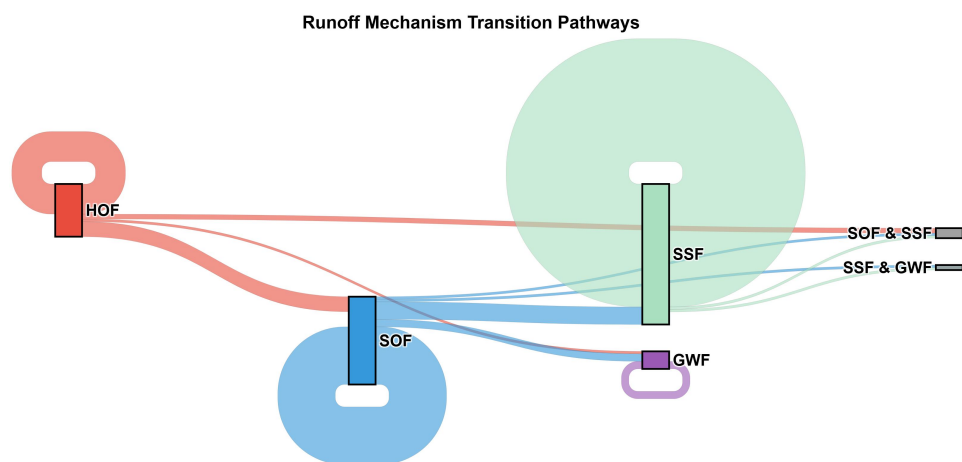


331 environments. HOF-dominated catchments are found across all aridity classes, with the largest
332 proportion in semi-arid climates, followed by humid catchments. GWF-dominated catchments
333 are restricted to humid and semi-humid climates, with no occurrences in semi-arid or arid
334 regions.

335 **3.4 Transitions of dominant runoff generation mechanisms under increasing wetness**

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

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

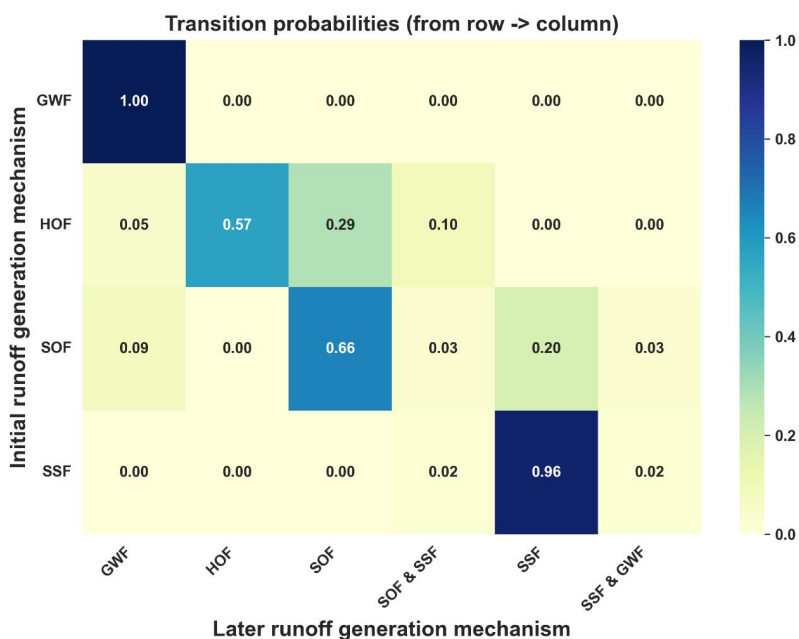




348 **Figure 6.** Sankey diagram illustrating observed transition pathways of dominant runoff
349 generation mechanisms under increasing wetness. Rectangular nodes represent runoff generation
350 mechanisms, with node size reflecting the total number of catchments reporting each mechanism.
351 Directed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

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

360 The conditional structure of these transitions is presented in Fig. 7, which shows transition
361 probabilities based on the number of catchments with a given initial dominant mechanism. For
362 HOF-dominated catchments, transitions to SOF account for approximately 29%, followed by
363 transitions to SOF–SSF (10%) and GWF (5%). For SOF-dominated catchments, the most
364 frequent transition is toward SSF (20%), with additional transitions to GWF (9%), SOF–SSF
365 (3%), and SSF–GWF (3%). For SSF-dominated catchments, transitions include shifts to SOF–
366 SSF (4%) and SSF–GWF (2%).



367

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

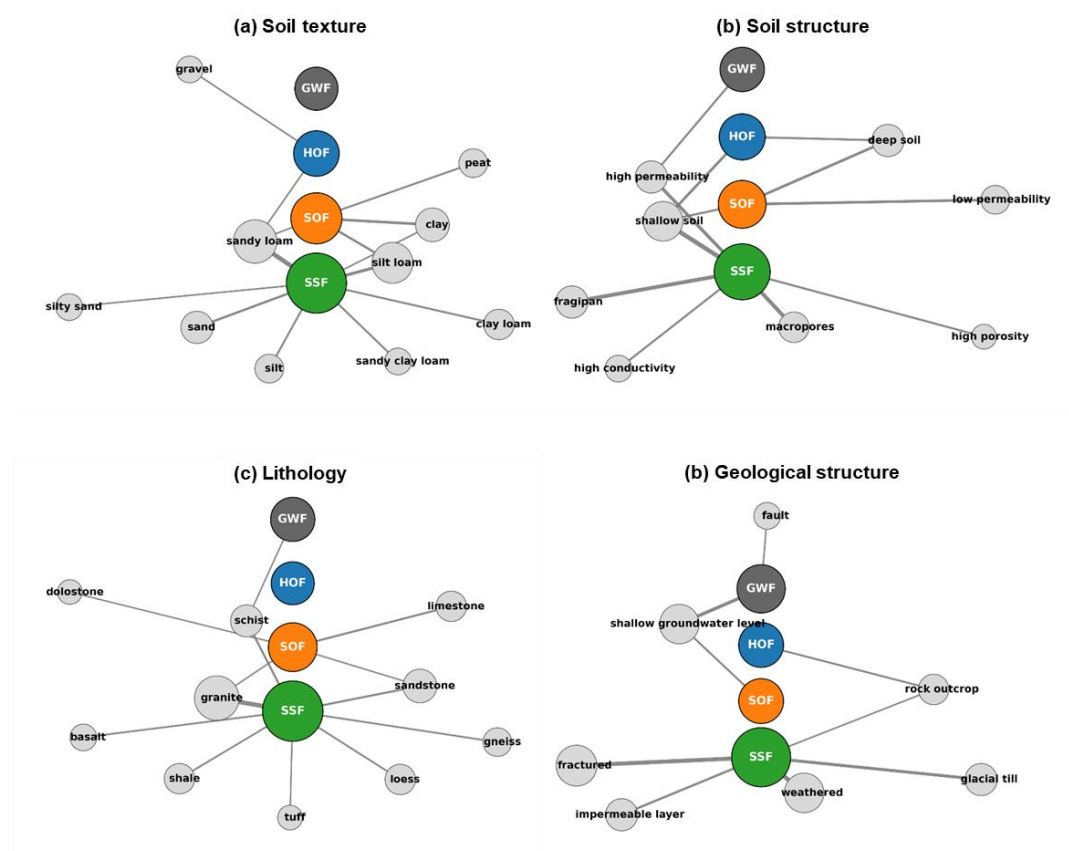
371 Across the compiled catchments, transitions are predominantly from surface-dominated
 372 mechanisms to subsurface- and groundwater-dominated mechanisms. Reverse transitions, from
 373 subsurface or groundwater-dominated flow to surface-dominated runoff, are rarely reported. To
 374 evaluate whether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

378 **3.5 Soil–geology fingerprints of runoff generation mechanisms**

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



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



387

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

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



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

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

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

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

416 **4. Discussion**

417 **4.1 What do runoff thresholds represent across studies?**

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

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



428 correlate with antecedent wetness, soil moisture, or groundwater levels, suggesting that
429 precipitation primarily triggers events rather than directly controlling regime shifts (Ali et al.,
430 2015; Ross et al., 2021; Tromp-van Meerveld and McDonnell, 2006a, b).

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

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

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

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



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

460 **4.2 Why do thresholds differ across mechanisms and catchments?**

461 Differences in runoff threshold behavior across mechanisms and catchments primarily stem
462 from how hydrologic connectivity develops within structurally constrained landscapes, rather
463 than differences in rainfall forcing alone. Soil and geological structure define the subsurface
464 architecture through which water is stored and transmitted, regulating both the rate of
465 connectivity increase with wetness and the flow pathways activated (Blume and Van Meerveld,
466 2015; McGuire and McDonnell, 2010).

467 The soil–geology fingerprints identified in Section 3.5 show that dominant runoff
468 mechanisms occupy distinct regions of structural attribute space. HOF-dominated catchments are
469 typically characterized by shallow soils, coarse surface materials, and limited storage capacity
470 (Kampf et al., 2018; Lana-Renault et al., 2013; Liu et al., 2022; Nanda and Sen, 2021),
471 conditions that favor rapid infiltration limitation during high-intensity rainfall. SOF, on the other
472 hand, emerges in settings with deeper, fine-textured soils and low-permeability substrates (Birkel
473 et al., 2017; Camporese et al., 2014; Frei et al., 2010; Meyles et al., 2003; Penna et al., 2010;
474 Steenhuis et al., 2013), where vertical storage accumulation leads to near-surface saturation and
475 expansion of connected source areas. SSF and GWF are linked to more complex subsurface
476 structures, such as permeability contrasts (Graham et al., 2010; Patankou et al., 2004; Wang et al.,
477 2022a), preferential flow networks (Detty and McGuire, 2010; Haga et al., 2005; Lee and Kim,
478 2020; Zehe et al., 2007; Zillgens et al., 2007), fractured or weathered bedrock (Birch et al., 2021;
479 Chappell et al., 2017; Cuomo and Guida, 2016; Nanda and Safeeq, 2023; Sahraei et al., 2020; Ye
480 et al., 2023), and shallow groundwater tables (Cuomo and Guida, 2016; Gao et al., 2024; Graeff
481 et al., 2009; Meyles et al., 2003; Scaife et al., 2020), all of which facilitate lateral and vertical
482 connectivity at depth.

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



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

490 In this structurally constrained context, the mechanism reorganizations observed in Section
491 3.4 exhibit a pronounced directional tendency under increasing wetness. Responses most
492 commonly evolve from HOF to SOF, and subsequently to SSF or GWF. This tendency
493 corresponds to the sequential activation of connectivity pathways as storage elements fill—from
494 surface runoff with limited storage, to saturation-driven overland flow, and ultimately to lateral
495 and vertical subsurface transmission once internal hydraulic linkages are established (Blöschl,
496 2022; Cain et al., 2022; Lana-Renault et al., 2013; Saffarpour et al., 2016; Schnabel and Gómez-
497 Gutiérrez, 2013). However, mechanisms frequently coexist, and dominance may shift gradually
498 rather than abruptly, with alternative pathways emerging due to structural features like soil pipes
499 or highly conductive bedrock.

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

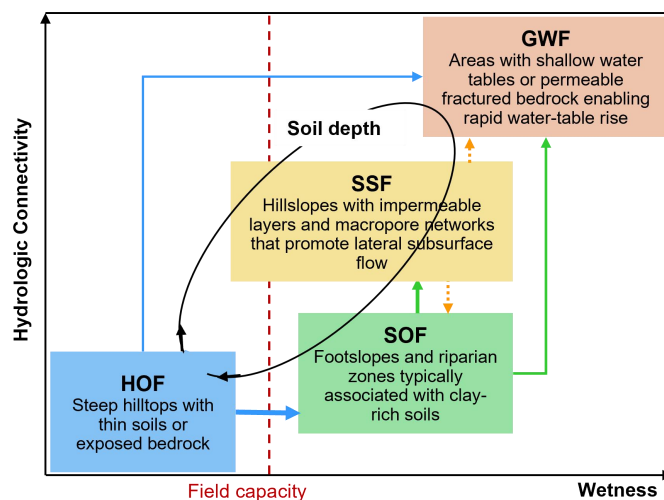
507 It should be noted that humid catchments are overrepresented in the reviewed dataset,
508 potentially biasing the apparent dominance of subsurface and groundwater transitions. While
509 directional reorganization remains evident within individual aridity classes, the limited number
510 of arid and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

511 **4.3 A revised conceptual framework for storm runoff generation**

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



517 catchment states, and relatively stable structural constraints (Genxu et al., 2017; Graham et al.,
 518 2010; Ross et al., 2021; Wang et al., 2022b; Wilson et al., 2017; Zimmermann et al., 2014).



519

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

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

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



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

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

549 Rainfall remains a necessary trigger for stormflow generation but does not solely determine
550 runoff response. Identical rainfall events can induce negligible runoff or abrupt regime shifts
551 depending on antecedent wetness and subsurface connectivity, reconciling the use of rainfall-
552 based and composite threshold indicators with consistent evidence that internal state is key to
553 explaining nonlinear behavior (Cain et al., 2022; Jin et al., 2020; Lee and Kim, 2020; McMillan
554 and Srinivasan, 2015; Nanda and Safeeq, 2023; Redding and Devito, 2008; Williams et al.,
555 2019). Thus, thresholds reflect occurrence conditions—specific combinations of triggering
556 rainfall and internal state—rather than intrinsic properties of rainfall alone.

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



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

575 **5. Conclusions**

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

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

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



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

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

608 **Data availability**

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

612 **Author contribution**

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

615 **Competing interests**

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

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851 **Appendix A.**

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

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



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



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



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



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

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

Original terms reported in literature	Standardized descriptor used in this study
shallow regolith, thin soils, shallow soils, shallow earth	shallow soil
deep permeable soil, thick soil profile, thick organic matter layer, deep loess	deep soil
high hydraulic conductivity, high infiltration capacity low hydraulic conductivity shallow impermeable horizon	high conductivity low conductivity 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 macropores, macroporous	shallow groundwater level macropores
low permeability substrate, low-permeability layer, low permeability soils	low permeability
high permeability, highly permeable soils	high permeability

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