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Title: Assessing the prevalence, timing, and rapidity of transitions between hydrological extremes and their relation to meteorological extremes in the conterminous United States

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Abstract. Rapid shifts between droughts and floods, termed hydrological whiplash, challenge water management, yet their timing and drivers remain poorly understood at continental scales. While drought-to-flood (DtF) transitions have received growing attention, flood-to-drought (FtD) transitions—though rarer—pose distinct operational challenges that are less well characterized. These wet-to-dry shifts can disrupt post-flood recovery, strain warm-season water demands, and create compounding risks for infrastructure and water quality. We analyzed daily streamflow records from 3,219 USGS streamgages (1981-2024) to characterize both DtF and FtD transitions across CONUS, with particular emphasis on understanding why these transitions are not symmetric inverses of each other. We test a wide variety of hydrological extreme transition definitions to examine the sensitivity of the number of transitions identified and their rapidity. Additionally, we identify a subset of transitions that may be impactful based on the maximum change in percentile magnitude during a transition. DtF transitions are faster than FtD transitions, and short-term (<= 30-days) transitions in both directions are concentrated in the Northeast, Northwest, and Rocky Mountains regions. Short-term DtF transitions are additionally concentrated in southern California and along the line from North Dakota down to Texas where precipitation approximately equals potential evapotranspiration. We find direction-specific controls: snow-dominated, urban, regulated, and minimally disturbed basins show the most frequent impactful DtF transitions, while regulated basins are most prone to impactful FtD transitions. Rapid and impactful transitions make up a substantially larger fraction of DtF transitions than FtD transitions across nearly all basin types. A key finding is that hydrological and meteorological whiplash rarely coincide: only 19-24% of hydrological extreme transitions co-occur with hydroclimate whiplash, revealing that basin storage, regulation, and routing processes create a fundamental decoupling between climate forcing and streamflow response. Our findings highlight the need to better understand quick hydrological transitions under increasing hydroclimatic volatility, particularly the understudied FtD direction, and the mechanisms by which anthropogenic modifications reshape the hydrological whiplash risk.

Key points:

1. DtF transitions are generally quicker than FtD transitions.
2. Transition characteristics are highly dependent on event definitions, but consistent patterns appear across definitions.
3. Greater fractions of DtF transitions are under 30 days for the Northeast, Northwest, and Rocky Mountains regions as well as southern California and along the P/PET ≈ 1 line from North Dakota down to Texas.
4. Fast DtF and DtF transitions peak in last winter and early spring (Feb-April)
5. Sub-seasonal transitions are most common in basins that are snowy, minimally altered, or regulated.
6. Rapid and impactful transitions make up a substantially larger fraction of DtF transitions than FtD transitions across nearly all basin types.
7. Only ~19-24% of hydrological whiplash events co-occur with meteorological whiplash.

Key words: hydrological whiplash, drought-to-flood transitions, flood-to-drought transitions, streamflow variability, hydrological extremes, drought, flood

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1 Introduction

Recent decades have seen increasing frequency, severity, and impacts of hydrological extremes, such as floods and droughts, drawing attention from scientists, policymakers, and the public (NCEI, 2024). Opposite extremes occurring in quick succession have led to significant challenges for communities (Rashid and Wahl, 2022; Barendrecht et al., 2024). These trends align with hydrological intensification, where the global water cycle becomes more variable, with more intense rainfall, longer dry spells, and higher evapotranspiration (Huntington, 2006; Kirchmeier-Young and Zhang, 2020; Ficklin et al., 2022). There is now a growing body of literature studying drought-to-flood (DtF) and flood-to-drought (FtD) transitions together rather than assessing individual extremes independently. While work assessing wet-to-dry and dry-to-wet meteorological states is more established (Li et al., 2023; Na and Najafi, 2024; Puxley and Martin, 2025; Swain et al., 2025, Mullens and Engström, 2025), a growing number of studies now focus on extreme transitions specifically in hydrological time series (Matanó et al., 2024; Götte and Brunner, 2024; Barendrecht et al., 2024; Hammond et al., 2025; Yang et al., 2025; Anderson et al., 2025).

He and Sheffield (2020) provide a comprehensive global assessment from 1950–2016 using event coincidence analysis, a method that quantifies simultaneity between climatic events through user-defined time lags and tolerance windows (Donges et al., 2015; Siegmund, Siegmund, and Donner, 2017). Their results show that 5.9% and 7.6% of global land area exhibited statistically significant “drought–pluvial seesaw” behavior during spring–summer and fall–winter, respectively, with roughly 11% of global droughts followed by pluvials in the next season. Stevenson et al. (2022) further project that 21st-century hydroclimate will be characterized by shifting baselines and more frequent extremes, potentially amplifying such compound events. Swain et al. (2025) describe hydroclimate whiplash as the rapid shift between extreme wet and dry conditions and show that its frequency has already increased due to rising global temperatures and is projected to intensify with continued warming.

Rapid transitions between hydrological conditions, such as flash flooding during drought, strain water-resources management by compressing decision windows and increasing unpredictability (Barendrecht et al., 2024; Ward et al., 2020). Water management can also reshape extremes in unintended ways: efforts to reduce one hazard may heighten vulnerability to the other, underscoring the need for standardized attribution methods and comprehensive datasets (Kreibich et al., 2019). For example, irrigation withdrawals in California’s Central Valley have prolonged drought severity and duration by up to 100%, doubling the likelihood of extreme events like the 2014 drought (He et al., 2017), while targeted flood- or drought-focused strategies can shift risk profiles and amplify the opposite hazard (Mazzoleni et al., 2021). Similarly, historical flood-control measures that rapidly convey water downstream have contributed to headwater drying (Holden and Shiferaw, 2004), and reservoir operations optimized for drought preparedness can reduce flood-buffering capacity (Di Baldassarre et al., 2017; Mateo et al., 2014). These coupled transitions, especially in fully allocated basins with limited storage, directly affect water availability and challenge infrastructure such as reservoirs and irrigation systems (Zaniolo, Fletcher, and Mauter, 2023; Christian et al., 2024). Managing such conditions becomes even more difficult in DtF situations, where operators must simultaneously capture inflows, prevent floods, and maintain adequate storage (Harpold, Dettinger, and Rajagopal, 2017).

As the hydrological cycle intensifies, infrastructure may struggle to meet multiple objectives, highlighting the need for actionable science to guide water management decisions (Ficklin et al., 2022; Henn et al., 2020; Simeone et al., 2024). Sequential events—such as a drought followed by a flood or vice versa—are often more difficult to recover from than single extremes (Brunner et al., 2021; Ward et al., 2020). Sub-seasonal and especially rapid transitions create periods of reduced predictability, complicating efforts of water and emergency managers to coordinate timely responses. These transitions can place additional stress on infrastructure and degrade water quality through increased nutrient loads, sediment transport, and other pollutants.

Large-sample studies are beginning to shed light on how these events vary across basin types. Götte and Brunner (2024) show that DtF transitions in the United States vary in length and spatial distribution, with snowmelt acting as the main driver in high-elevation basins. Reservoir management was found to reduce short DtF transitions, particularly in snowmelt-driven basins. Similarly, Muñoz-Castro et al. (2025) demonstrate that hydrologic models often fail to capture DtF transitions because performance hinges more on reproducing streamflow timing than on general efficiency scores, and that model structure, basin characteristics, and climate forcing critically shape predictive success, especially in semi-arid mountain regions. Other recent studies have documented hydrological extreme transitions across the United States using annual or multi-year indicators of water-year conditions and cumulative deficits and surpluses (Li et al., 2025; Maharjan et al., 2025). These efforts have been critical for establishing the growing prevalence and societal relevance of hydroclimatic whiplash at regional to continental scales. A continental-scale perspective enables comparison across a wide diversity of hydroclimatic regimes, watershed storage behaviors, and land-use conditions. This scale also allows for

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identifying whether observed transition characteristics are driven by local processes or represent consistent, emergent patterns across contrasting settings.

Although FtD transitions are less common and less studied, they also present significant challenges for water availability and management with distinct operational challenges. A future with more rain and less snowmelt could produce high winter or early spring flows followed by low early summer flows, disrupting irrigation systems historically aligned with snowmelt runoff timing. Earlier snowmelt extends the duration water must be stored, intensifying conflicts between retaining storage for later downstream use and reserving capacity for potential flood protection during subsequent rain or rain-on-snow events. In some cases, this pattern manifests as flash droughts (Christian et al., 2024). Following floods, reservoirs may be forced to release excess water to prevent damage, reducing storage just as drought conditions emerge. During drought, water availability declines, further complicating efforts to balance immediate low-flow needs with maintaining reserves for the future. The wet-to-dry direction is not simply the inverse of dry-to-wet: post-flood drawdown requirements, warm-season demand, and ecological stress pathways of FtD sequences differ fundamentally from DtF sequences.

Rapid wet-to-dry shifts can disrupt agricultural production, degrade ecosystem health, and impair water quality (Swain et al., 2025; Loecke et al., 2017; Chen and Wang, 2023)—especially in regions with fully allocated or highly regulated resources (Götte and Brunner, 2024; Simeone et al., 2024). For example, Feng et al. (2024) show that intense rainfall from flood events can drive increased nutrient runoff, and subsequent droughts can extend the residence time of these waters, resulting in optimal conditions for harmful algal blooms. Rapid FtD and DtF transitions impose infrastructure challenges across both time and spatial scales, affecting short- to long-term decision-making (from operational reservoir releases and stormwater management to long-range planning of dams and water-supply systems) and spanning local to national scales where coordinated, multi-jurisdictional infrastructure strategies are required to manage rapidly shifting hydrologic extremes (Li et al., 2025; Maharjan et al., 2025; Granata and Di Nunno, 2026; Hammond et al., 2025). Inadequate infrastructure or outdated management strategies can further compound the difficulties of effectively responding to such transitions.

Methodological clarity is also essential for understanding DtF and FtD transitions. Anderson et al. (2025) show that methodological choices, such as threshold definitions and time windows, strongly shape the detection, timing, and characteristics of DtF transitions, especially in seasonal flow regimes, and that commonly used methods may miss historically impactful events. This highlights the importance of consistent definitions and robust approaches to identifying hydrological whiplash.

The work that follows is unique in its exploration of both DtF and FtD transitions, providing a more complete understanding of hydrological whiplash. Using a large sample of streamgages across the United States, we categorize sites by land use and management types, including agricultural, urban, and heavily flow-regulated systems. We also introduce a secondary threshold to identify "impactful transitions," focusing on transitions that involve substantial hydrologic state changes. By examining the seasonality of transitions of varying lengths, we capture important temporal patterns that influence water management challenges. Finally, we assess the degree of overlap between meteorological whiplash and hydrological whiplash, offering insight into the alignment, or divergence, between climatic drivers and streamflow responses.

Our study addresses four overarching questions:

1. Where do sub-seasonal hydrological extreme transitions occur most frequently, and how sensitive are these patterns to the definitions used to identify them?
2. How do the properties of DtF versus FtD transitions differ in terms of timing and seasonality?
3. What role do basin characteristics, including human activities, play in shaping these transitions?
4. To what extent do hydrological and hydroclimate whiplash events coincide, and what does this reveal about watershed filtering of climate signals?

The goals of this work are to improve understanding of when and where these transitions have occurred, what length of transitions can be expected in different regions and for different classifications of sites, and to provide a dataset of identified transitions. This dataset is also intended to provide an identified transition database that could be used to examine hydrologic model performance during periods of rapid transition as well as assessment of impacts on infrastructure, water quality, and water management in the context of compound drought and flood events.

2 Methods

2.1 Streamflow Data

We selected 3,219 U.S. Geological Survey (USGS) streamgages based on two criteria: (a) streamflow time series were required to include at least 95% of daily observations in each year and (b) streamgages were required to have at least 8 of 10 complete years for decades from 1981-2020 (e.g., 2000–2009 and 2010-2019) following the methods in Simeone (2022). We obtained daily streamflow data from 1981-2024 from the USGS National Water Information System (NWIS, U.S. Geological Survey, 2026) using the R package dataRetrieval (Hirsch and De Cicco, 2015; R Core Team, 2024). We computed streamflow percentiles with the unbiased Weibull plotting position (Stedinger et al. 1993) for daily flow using two approaches: (a) fixed—all flows in the period of record were used to calculate one fixed threshold and (b) variable— unique thresholds were calculated for each day of the year using only the 7-day moving average streamflow values for a 7-day window surrounding that day from all years of record. Fixed and variable percentiles were calculated in reference to the 1981-2020 period consistent with previous research (e.g., Hammond et al. 2022; Simeone et al. 2024). We implemented a modified version of the combined threshold level and continuous dry period methods (Simeone et al. 2024; Van Huijgevoort et al. 2012) to handle the zero-flow measurements (<0.00028 m^3/s; <0.01 ft^3/s). This method breaks ties between zero-flow days for percentile rankings based on the number of preceding zero-flow days, where days with more preceding zero-flow days received lower percentile rankings.

2.2 Event and Transition Identification, and Sensitivity to Criteria Used

We explore an array of different drought and flood definitions (Text S1), as these definitions have been shown to impact whiplash results (Anderson et al., 2025). We tested a broad range of drought and flood identification criteria (Fig. S1, Fig. S2, Fig. S3). For droughts, we evaluated 18 combinations of: (1) percentile thresholds of 10th, 15th, and 20th; (2) inter-event periods of 5, 15, and 30 days; and (3) minimum drought durations of 5, 15, and 30 days, with the constraint that minimum duration could not be shorter than the inter-event period. For floods, we tested five definitions: fixed percentile thresholds of 98th, 99th, and 99.5th, and peaks-over-threshold (POT) methods calibrated to identify either one or two events per year on average.

Throughout the manuscript, we refer to three representative definitions. The strict definitions use the 10th-percentile drought threshold with a 30-day minimum duration and 5-day inter-event period, and the 99.5th-percentile flood threshold. The lenient definitions use the 20th-percentile drought threshold with a 5-day minimum duration and 5-day inter-event period, and a POT-2-events-per-year flood threshold. The study definition, used in our main analyses, applies a 10th-percentile drought threshold with a 15-day minimum duration and 5-day inter-event period, and a POT-1-event-per-year flood threshold. These selections provide balanced detection rates across the conterminous United States (CONUS) and minimize spatial biases in event identification.

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After this testing, we selected our definitions to identify similar numbers of drought events and flood events (1 event per year on average) so that our data are balanced across FtD and DtF transitions. This makes our results more likely to be indicative of process differences rather than simply a larger number of events of one type or the other. We define droughts as periods where the variable percentile is below the 10th percentile and use an inter-event time and volume criterion (WMO, 2008) to pool drought events where the interevent period is 5 days or less or less than 10% (a fraction of 0.1) of the drought volume (in percentile units). We additionally impose a minimum drought duration of 15 days. We identify floods by setting a fixed percentile threshold for each site, by using a peaks-over-threshold (POT) method set to identify an average of one flood event per year. We imposed a 15-day separation between flood events.

From each drought event, we identify the transitions as the period until the subsequent flood event. Multiple drought period transitions that occurred without an intervening flood event were treated as ended with the same flood event. We apply the reverse to flood events. This provides us with an empirical distribution of the transitions from each event to the next event of the opposite type including the transition duration and the properties of each event. We identify transitions that take place in ≤90 days as sub-seasonal, ≤30 days as short-term transitions, and ≤14 days as rapid transitions (Anderson et al., 2025). For rose seasonality plots, the seasonal timing was selected as the month of the end of the first event in a transition.

We analyzed the full distribution of hydrological transitions prior to focusing on rapid and sub-seasonal events because, from an operational perspective, the ultimate duration of a transition is unknown while it is unfolding. By first characterizing the entire spectrum of transition lengths, we establish the natural range of hydrologic evolution across basins, enabling rapid events to be evaluated relative to typical persistence and improving interpretation of unfolding conditions in real time. Examples of these transition patterns, including 2023 DtF and FtD events are shown in Fig. 1. All processed drought, flood, and transition datasets used in this analysis are available in Simeone and Hammond (2026).

We define an impactful hydrological extreme transition as one that occurs within 90 days and involves at least a 50-percentile shift in fixed streamflow percentile space, ensuring that identified events represent substantial hydrologic state changes rather than simple threshold crossings or seasonal re-ranking. Because fixed percentiles are calculated relative to the full historical flow distribution, a 50-percentile shift represents movement across half of a site's flow regime, signaling a transition between distinctly different hydrologic conditions. Although such a shift does not correspond to a uniform change in discharge or annual flow volume across basins, it represents a consistent change in relative hydrologic rarity and movement through different portions of the flow duration curve. For example, transitions from the 10th to 60th percentile may indicate dramatic relative increases in discharge in arid or flashy systems, while shifts from the 30th to 80th or 40th to 90th percentile may correspond to large absolute increases and approach bankfull conditions in humid basins. By defining impactfulness in percentile rather than discharge space, we enable comparability across diverse hydrologic regimes while capturing transitions that are large relative to local variability. Such swift change in the context of the historical flow range can challenge reservoir operations, culvert capacity, stormwater systems, and flood forecasting frameworks, and may generate operational disruption even when annual flow volumes remain near average, because risk arises from abrupt reconfiguration rather than cumulative surplus or deficit.

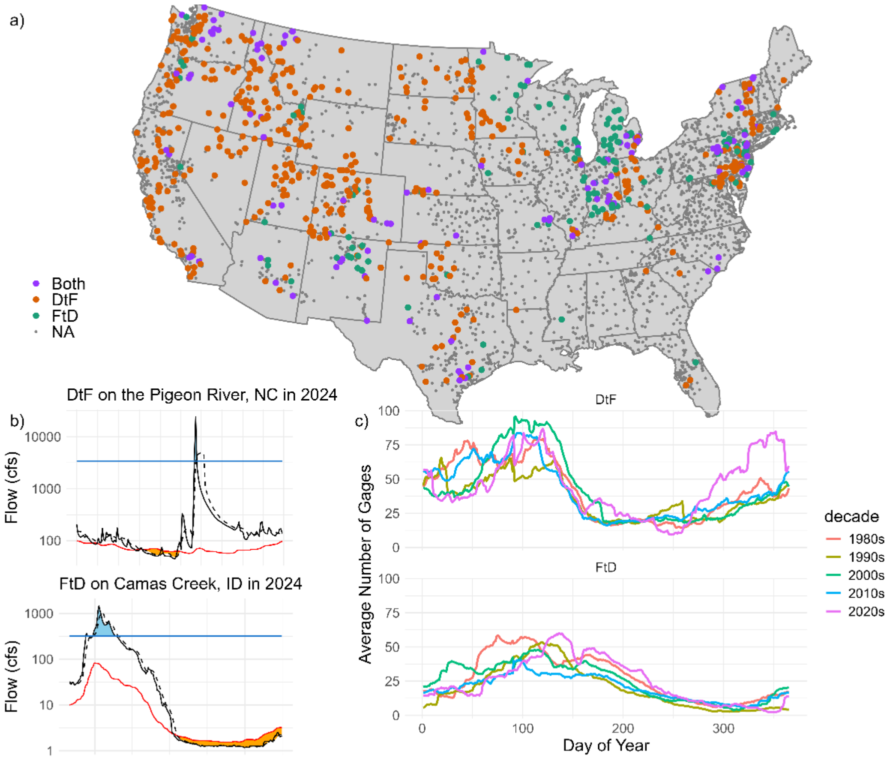

Figure 1: Map of transitions of less than 90 days that occurred in 2023 (a). Example drought-to-flood (DtF) transition on the Pigeon River in North Carolina (03456991; U.S. Geological Survey, 2026) as a result of Hurricane Helene (b). Example flood-to-drought (FtD) transition on Camas Creek in Idaho (13141500) (b). Panel b shows flow in black (1-day is solid and 7-day is dashed), and the drought and flood thresholds in blue and red respectively. Average number of sites experiencing transitions (DtF and FtD of less than 90 days for each day of the year for each decade (c).

2.3 Basin Characteristics

We split streamgages into 12 hydrologic regions (Fig. S4) defined by their correlation in monthly flows among the minimally altered streamgages in the Hydro-Climatic Data Network (HCDN; Lins, 2012), following approaches by McCabe and Wolock (2022) and Hammond et al. (2022). Streamgages not within the HCDN were attributed to the region of the nearest HCDN streamgage (Simeone et al., 2024). To further assess the influence of basin characteristics on hydrological whiplash, we categorized basins using several criteria. First, basins were classified as energy- or water-limited (wet/dry) based on whether the ratio of potential evapotranspiration to precipitation was greater or less than one. Precipitation type (rain versus snow) was determined by whether peak snow water equivalent accounted for more than 25% of total precipitation. Basins were also grouped by predominant land use following Dudley et al. (2020) using the National Land Cover Database (Fry et al., 2011). Specifically, HCDN reference basins were defined as those with minimal anthropogenic influence (Lins, 2012). Agricultural basins were characterized by greater than 20% agricultural land use, less than 60 days of upstream regulation, and less than 6% urban land use. Urban basins were defined as greater than 10% developed, with less than 2% agricultural use and less than 60 days of upstream regulation. Regulated basins had more than 180 days of upstream storage, less than 2% developed land use, and less than 2% agricultural land use (Falcone, 2011). Basins not fitting any of these categories were classified as other (Dudley et al., 2018; Hodgkins et al., 2019). In addition, basins were categorized by synchronicity, defined as asynchronous, neither, or synchronous depending on whether PET synchronicity was less than –0.4, between -0.4 and 0.4, or greater than 0.4, respectively, where synchronicity was calculated as the correlation between monthly P and PET, using values obtained from gridMET (Abatzoglou, 2013). Finally, flow concentration was classified as concentrated or event-dominated based on whether input seasonality was greater or less than 0.5 (Hammond, 2024).

2.4 Hydrological vs Meteorological Whiplash

We investigated connections between hydrological and meteorological whiplash, focusing on levels of co-occurrence, by comparing our identified transitions to the meteorological wet-to-dry and dry-to-wet transitions identified from standardized precipitation evapotranspiration index anomalies from Swain et al. (2025). Events from Swain et al. (2025) were aggregated from gridded rasters to stream watersheds, with each event mapped as the fraction of the watershed impacted. Because Swain et al. (2025) aggregated events to seasonal time steps, we aligned our transitions—restricted to those lasting less than 90 days—with theirs based on the season in which the transition ended (winter: January–March; spring: April–June; summer: July–September; fall: October–December, not that using the season the transition ended is different from the start of the transition which we used for rose plots). Meteorological transitions had to impact 10% or more of a basin to be paired with each hydrologic record. For each transition type (FtD, DtF, wet-to-dry, dry-to-wet), we then calculated the fraction of transitions that had a comparable transition in the other system occurring within one seasonal timestep. For example, we assessed what proportion of hydrological DtF transitions coincided with a meteorological dry-to-wet transition during the same season or in the immediately preceding or following season.

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We further explored the connections between meteorological and hydrological transitions by identifying the maximum increase and decrease in streamflow percentiles for each site (fixed and variable) during each season and the preceding 90 days. We then compared the maximum changes in streamflow percentiles from seasons where there were meteorological or hydrological transitions against the average percentile changes across the full record for each site, to identify if increase and decreases in streamflow percentiles are larger or smaller during event transitions compared to average site conditions. Using this approach, we identified where meteorological and hydrological sub-seasonal transitions overlapped, expressed as the fraction of each transition type with a corresponding transition in the other system within one season.

3 Results

3.1 Case-Study Hydrographs

Before presenting the large-sample spatial and temporal patterns, we provide several hydrograph-based examples to illustrate how different drought and flood definitions operate in practice and how real transitions manifest across contrasting basin types. Fig. 2 shows example rapid and sub-seasonal transitions at 6 streamgages and how different drought and flood definitions impact the identified events and the transitions between them. In 2011, Hurricane Irene caused a rapid shift from DtF conditions on the Androscoggin River in Maine (Fig. 2a). This transition highlights a straightforward example of a DtF transition. Although Maine was not impacted as much as other parts of the region, this was a notable flooding event causing significant regional damage (Suro et al., 2015). Transition times from DtFs are 7-8 days. Both the lenient and study droughts end on 8/22. The lenient and study floods start on 8/29 and strict flood starts 8/30. This event is not classified as a drought with the strictest definition, so using that definition does not identify this as a transition. Lenient and study flood conditions were also present in late April, with transition times ranging from 85-100 days to lenient and study drought conditions, but in a case where there is neither drought nor flood in the strictest definitions.

In July 2025, the Guadalupe River in Texas experienced a rapid and deadly DtF transition (Fig. 2b; NOAA, 2025). This transition was extremely rapid, just one day, and the daily unit values we use through this paper (changing from 2.3ft of stage to 12.8 ft of stage from 7/3 to 7/4) do not capture the speed or severity of this transition from less than 3ft at 4:15am to greater than 33ft at 6:30am on July 4th 2025 (NOAA, 2025, Fig. S13). This transition is much more dramatic than any historical transformations in the streamgage record (Fig. S13). Out of 92,108 total DtF transitions identified in this paper, there are only 95 (0.1%) transitions

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where flow of <1st percentile transitioned to >99th percentile within a single day, as happened in on the Gudalupe River in 2025. Of the 95 transitions, 10 occurred in the Northern Mid-Atlantic region and 12 occurred in the Southwest region, but they most frequently occurred in the South Central region (27 events; Fig. A13).

In January 2009, there was a rapid FtD transition in the urban Huge Creek near Wauna, Washington (Fig. 2c). The FtD transition times at this streamgage are similar regardless of definitions (12-15 days). However, using the study and lenient definitions, there is additionally a preceding drought event with a rapid transition (9-13 days), which does not occur with the strict drought definition. This reframes the sequence as a brief, flashy flood event interrupting a prolonged drought, a dynamic that is masked when using the stricter drought definition.

In 2018, early spring snowmelt led to a flood (Mitchell, 2018) which was then followed by a summer drought on the Fish River near the Town of Fort Kent, Maine (Fig. 2d). While floods and droughts occur in all cases during this transition, the rate of change is much faster lenient drought and flood definitions (13 days) than it is with stricter (47 days) definitions or those we use in our study (42 days). The drought events persist much differently following the transition using different definitions. Additionally, the lenient definitions overlap at the start of this transition, highlighting some of the complexity of combining variable and fixed percentiles measures.

In 2012, there was a transition from flooding to a major flash drought in the Central Plains (Rippey, 2015). Fig. 2e shows this transition on the Caney River in Kansas, but other regional streamgages show a similar transition. Study and strict floods end on 4/30, and the lenient flood ends 5/1. However, start dates of droughts vary, with transition times ranging from 20-54 days. Additionally, with the study definition, the flash drought is 2 distinct droughts rather than one continuous one. The drought event on the Caney River also highlights the handling of zero flow days we use, because the 10th percentile flows (orange) hit zero for an extended period of the summer, and the 20th percentile flows (yellow) do so for a short period; however because the 2012 flows hit zero earlier and stay at zero throughout the remainder of 2012, they are considered a drought.

During 1992–1993, there were a series of quick hydrological transitions on the Bill Williams River below Alamo Dam in Arizona (Fig. 2f). Using the most lenient drought and flood definitions, there are 7 DtF or FtD transitions and one period of full overlap between the two. For the most lenient definitions, the fastest DtF transition is just 1 day and the fastest FtD transition is 7 days. For the strictest definitions, there is just one total transition in this period which is from DtF lasting 219 days. The transitions over this period at this

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streamgage highlight some of the potential difficulties of identifying whiplash events on regulated rivers and the importance of the selection of appropriate definitions for this task.

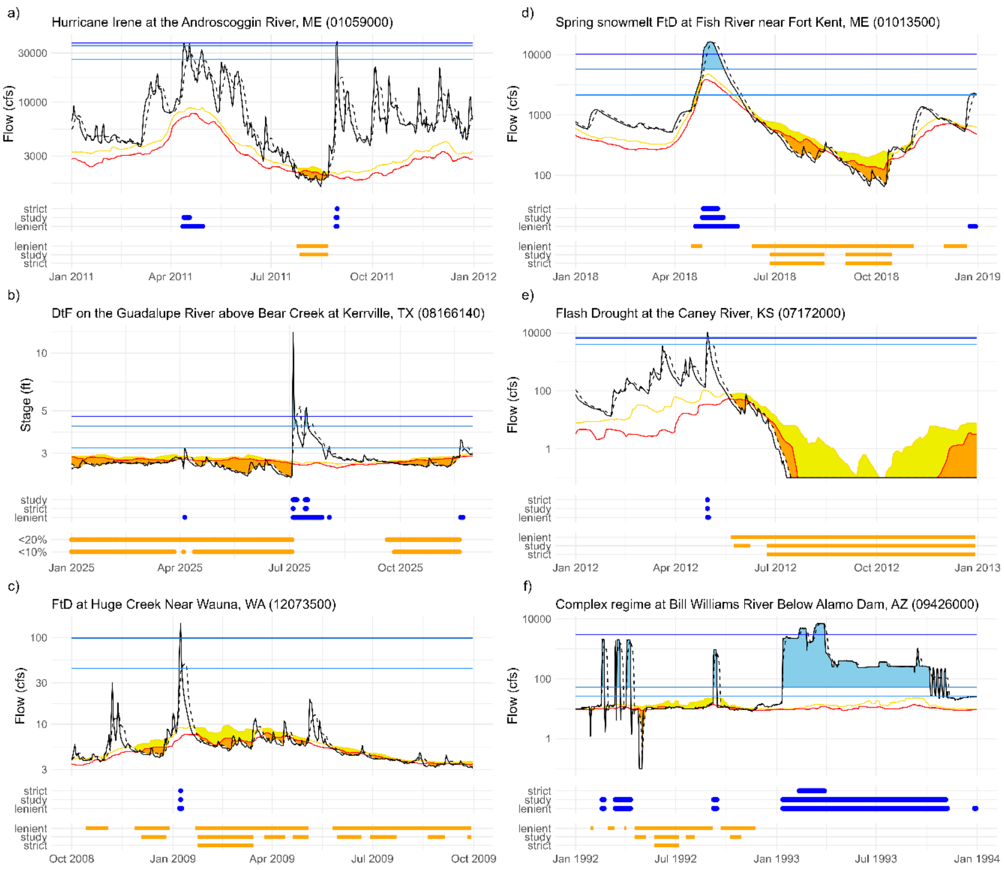

Figure 2: Case-study hydrographs for six examples of rapid and sub-seasonal transitions. Daily streamflows are in black and 7-day average streamflows are the dashed black line. Drought thresholds are shown for the 10th percentile (red with orange fill) and 20th percentile (yellow with yellow fill). Flood thresholds used in the study are shown as blue lines for 3 flood definitions, the most strict we considered (99.5th fixed percentile, darkest blue), the definition we use throughout this study (peaks-over-threshold 1 per year, intermediate blue), and the most lenient definition we use in this study (peaks over threshold 2 per year, light blue). Below the hydrograph, floods are identified for each of the 3 levels (strict, study as lenient) as the blue points. Drought periods are identified as orange points for a strict drought definition we use (10th percentile, 5-day inter-event threshold,

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and 30-day minimum drought length), the definition we use in the study (10th percentile, 5 day inter-event threshold, and 15-day minimum drought length), and the most lenient definition we use in the study (20th percentile, 5-day inter-event threshold, and 5-day minimum drought length). Note that for the Guadalupe River (b), we only use drought percentile thresholds because we do not have a full 40-year record for drought analysis at this streamgage (U.S. Geological Survey station numbers in parentheses; U.S. Geological Survey, 2026).

3.2 Characteristics of Transitions

To understand the characteristics of extreme event transitions, we map rates of occurrence of transitions under 30 and 90 days across CONUS (Fig. 3 a, b, f, g; Fig. S5a, b). More frequent sub-seasonal transitions occurred in both directions in the Northeast (a site median of 21.6% of DtF and 9.4% of FtD transition occur within 90 days), Northern Mid-Atlantic (19.4% and 7.0%), Rocky Mountains (24.3% and 6.8%) and Northwest (22.2% and 6.8%) regions than the national average. Many streamgages along the P/PET ≈ 1 line from North Dakota down to Texas and in southern California have relatively frequent fast transitions from droughts to floods. The rarest sub-seasonal transitions occur in the Southern Mid-Atlantic (13.6% and 2.4%), Southeast (14.3% and 2.4%) and Central Plains (15.9% and 2.2%). The Southwest (The difference in frequency of events under 90 days between the 25th percentile and 75th percentile (the IQR) was 13.4% for droughts and 10.0% for floods), Rocky Mountains (14.3% and 9.3%), and California and Interior West (15.3% and 6.8%) regions have the highest amounts of variability in the frequency of occurrence of sub-seasonal transitions across sites. DtF transitions are much faster (a site median of 18.4% under 90 days and 7.1% under 30 days) than vice versa (4.5% under 90 days and a median of zero under 30 days).

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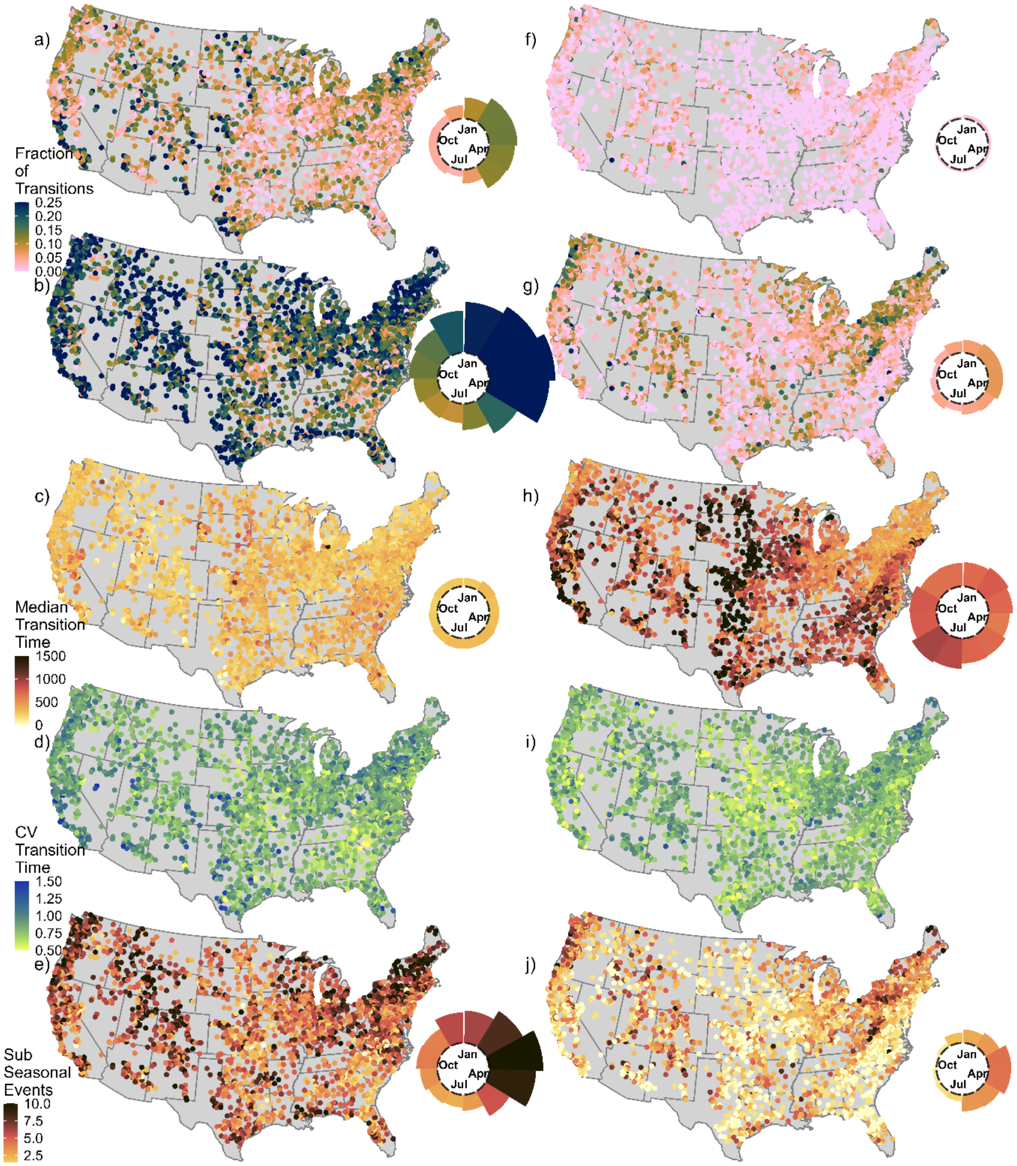

Figure 3: Row one: Fraction of transitions at each site that occur in less than 30 days for drought-to-flood (DtF) (a) and flood-to-drought (FtD) (f) transitions. Row two: Fraction of transitions at each site that occur in less than 90 days for DtF (b) and FtD (g) transitions. Row three: median transition times in days from droughts to floods (c) and from floods to droughts (h). Row 4: coefficient of variation for transition times from droughts to floods (d) and floods to droughts (i). Row 5: The number of sub-seasonal transitions at each site for

DtF (e) and FtD (j). Rose plots show the seasonality of transitions across seasons for each plot, based on the month of the end of the first event in a transition. Rose plot colors and bar heights are set to the same values as the map legends, except for the rose plot for events which is normalized by the number of sites and the number of months so that values are consistent with the maps.

Short-term and sub-seasonal transitions in both directions (FtD and DtF) occur most commonly during late winter and early spring, during the high-flow season of much of CONUS (Fig. 3 rose plots). For DtF transitions, the timing of these transitions likely corresponds with the occurrence of floods this time of year. For FtD transitions, early-season floods, followed by below-normal flows may yield shorter transitions. These seasonal patterns vary dramatically by region (Fig. S6, Fig. S7). Some regions are highly seasonal (Northeast, North Central, Rocky Mountains, Northern Mid-Atlantic), while others (Southwest, Central Plains, and Southern Mid-Atlantic) are much less so. Transitions from 2023 illustrate the occurrence of these transitions in recent times (Fig. 1a). Across the United States, hundreds of sites experienced sub-seasonal hydrologic transitions lasting less than 90 days, with DtF transitions more common than FtD transitions in both humid and arid regions.

Median times of all transitions (Fig. 3 c, h; Fig. S5c) are faster from DtF transitions (median of 291 days) than FtD transitions (median of 714 days). The North Central (322 days DtF and 1101 days FtD), Central Plains (318 days and 996 days), and California and Interior West (296 days and 1050 days) regions have the slowest median transition times. The Northeast (246 days and 392 days), Northern Mid-Atlantic (281 days and 435 days), Central Forests (262 days and 588 days), and Northwest (264 days and 554 days) regions have the fastest median transition times. Coefficients of variation of transition times are similar between floods to droughts (0.77) and droughts to floods (0.83).

Transition times are impacted by the number of drought events (a median of 29 events per site) and number of flood events (a median of 43 events per site) over our period of analysis (1981-2024). These numbers are not uniform across CONUS (Fig. S5e), and are dependent on the definitions used to classify events (Fig. S1, Fig. S2). A median of 42-44 flood events were observed per site for all regions except for the Southeast region, where a median of 39 was observed. The most drought events were observed in the Northeast (34 events), Northern Mid-Atlantic (31 events), and Southern Mid-Atlantic (31 events) regions, and the fewest drought events were observed in the North Central (25 events), Central Plains (27 events), and South Central (27 events) regions.

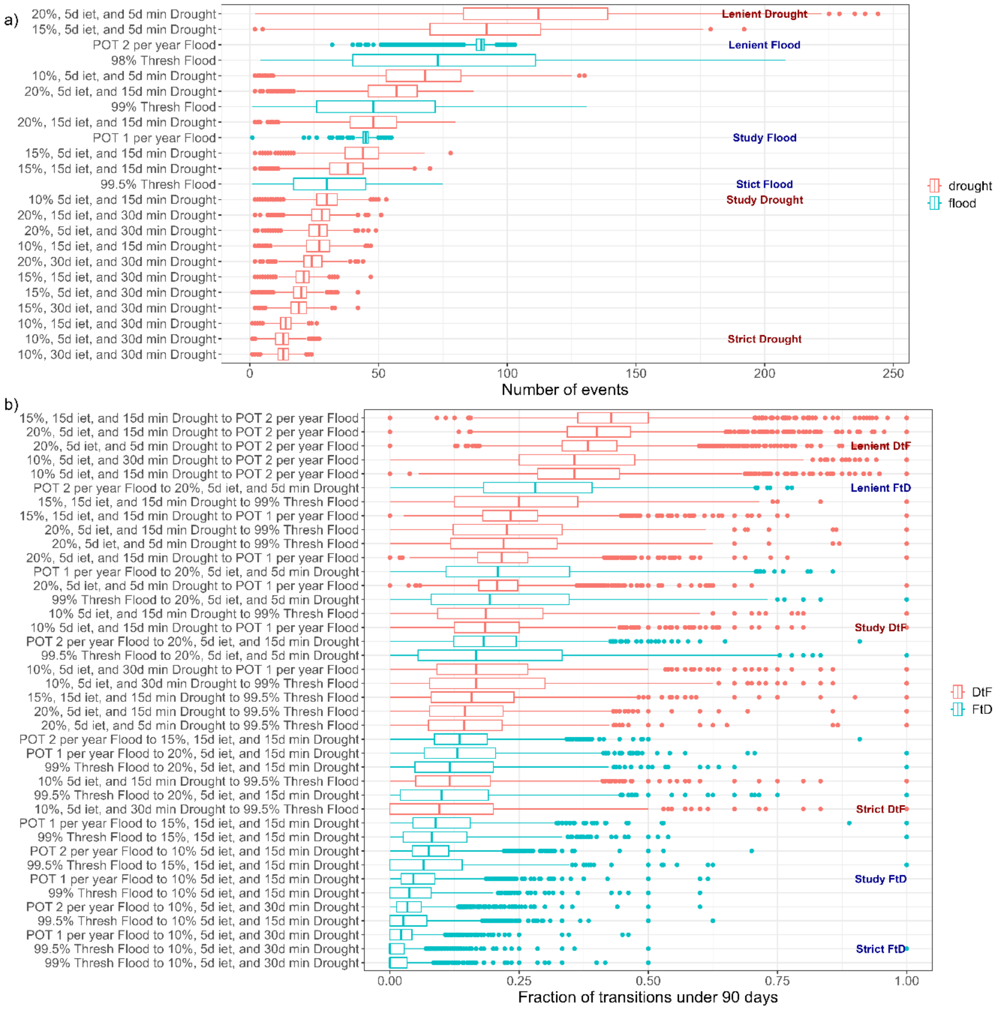

Figure 4: Event counts vary widely across different definitions of flood and drought events. Panel a shows box plots for the number of events per site for 18 different drought event definitions and 5 different flood event definitions. We also identify an example strict definition, and example lenient definition and the definition we use in the study for both floods and droughts. Panel b shows the fraction of transitions under 90 days for 4 different definitions of floods and 5 different definitions of droughts (20 combinations each of FtD and DtF). Panel b also highlights transitions between the strict, lenient, and study methods described in panel a. For each box plot the center line indicates the median, the box boundaries represent the interquartile range (IQR), and whiskers extend to the furthest data

point within 1.5 times the IQR from the box boundaries. Individual points represent outliers falling outside this range.

Figure 5: Maps of drought-to-flood (DtF) and flood-to-drought (FtD) transitions for selected lenient (the highest number of events), strict (the lowest number of events), and study (intermediate number of events) definitions of droughts and floods show that short-term

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DtF transitions are far more prevalent and spatially extensive than FtD transitions across all drought and flood definitions, particularly across the eastern and central United States. The flood definitions include the strictest definition we considered (99.5th fixed percentile), the definition we use throughout this study (peaks-over-threshold 1 per year), and the most lenient definition (peaks-over-threshold 1 per year). The drought definitions include a strict definition (10th percentile, 5-day inter-event threshold, and 30-day minimum drought length), the study definition (10th percentile, 5-day inter-event threshold, and 15-day minimum drought length), and a lenient definition (20th percentile, 5-day inter-event threshold, and 5-day minimum drought length).

Figure 4 indicates that combining methods with very different detection rates can strongly bias the relative prevalence and inferred timing of DtF versus FtD transitions. Despite substantial variability in absolute event counts across definitions, the fraction of short-term transitions (<30 days) remains consistently higher for DtF transitions than for FtD transitions across most definitions, demonstrating the robustness of this asymmetry. While absolute fractions of fast transitions vary with the strictness of event definitions, the broad spatial patterns remain remarkably consistent, indicating that the results are not driven by a single methodological choice (Fig. 5, Fig. 4). Lenient definitions generally increase the fraction of fast transitions, whereas stricter definitions reduce counts but preserve regional hotspots.

3.3 Basin Characteristics

We explored boxplots of the fraction of transitions that are impactful (occurring under 90 days and a ≥ 50% fixed percentile shift) and the median transition times across different basin characteristics to understand potential causes of transitions (Fig. 6). These patterns reveal that impactful transitions make up a substantially larger fraction of DtF transitions than FtD transitions across nearly all basin types (Fig. 6).

Snow-dominated basins (peak SWE/P ≥ 0.25) had higher frequencies of sub-seasonal DtF transitions, and these transitions were more common in dry (PET/P ≥ 1) snowy basins (21.9%) than wet snowy basins (20.8%). Wet and rainy basins had sub-seasonal DtF transitions 18.8% of the time. Wet basin types had equal frequencies of sub-seasonal FtD transitions (6.7%). Dry and rainy basins had the least frequent DtF (17.4%) and FtD (2.4%) transitions (Fig. 5a).

Management-relevant basin types show direction-dependent whiplash patterns. Across different land use / management classifications, we observed that minimally disturbed (HCDN, 21.4%), regulated (21.1%), and urban (18.9%) basins, have DtF sub-seasonal

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transitions more frequently then than agricultural (17.4%) and other unclassified (17.6%) basins (Fig. 6b). Regulated basins have the most frequent FtD transitions (7.3%). We also see that in particular smaller (≤100km^2) minimally altered basins have more frequent DtF transitions (25.0%) than medium (20.9%; >100km^2 and ≤1000km^2) or large (20.0%; >1000km^2) sized basins (Fig. S8c).

Patterns in the frequency of quick transitions vary across combinations of input concentration and climatic synchronicity (Fig. S8a). Input concentration represents how temporally concentrated rainfall and snowmelt are within the year, whereas synchronicity describes the seasonal alignment between precipitation and potential evapotranspiration (PET), with asynchronous systems characterized by out-of-phase peaks (e.g., winter precipitation and summer PET maxima). Basins with concentrated precipitation inputs have more frequent DtF transitions, and within those concentrated basins sub-seasonal DtF transitions are more common in asynchronous (21.4%) than synchronous basins (18.5%). In contrast, sub-seasonal FtD transitions are most frequent (6.7%) in basins with intermediate synchronicity and more evenly distributed flow regimes. These results suggest that both the seasonal phase relationship between water inputs and atmospheric demand and the temporal concentration of rainfall and snowmelt influence the likelihood and direction of sub-seasonal hydrological transitions.

Assessing patterns by region, impactful DtF transitions occur at least 20% of the time in minimally disturbed basins in many regions (Northeast, Northern Mid-Atlantic, North Central, Rocky Mountains, Southwest, South Central, California and Interior West, Northwest) and at agricultural basins in the Northern Mid-Atlantic, regulated basins in the Rocky Mountains, Southwest, North Central, and California and Interior West regions, and in urban basins of the California and Interior West region (Fig. S8d). FtD transitions also occur in greater than 5% of cases (about the national median) in all of those regions and land-use pairings except for minimally disturbed basins in the South Central and California and Interior West regions and urban basins in the California and Interior West region.

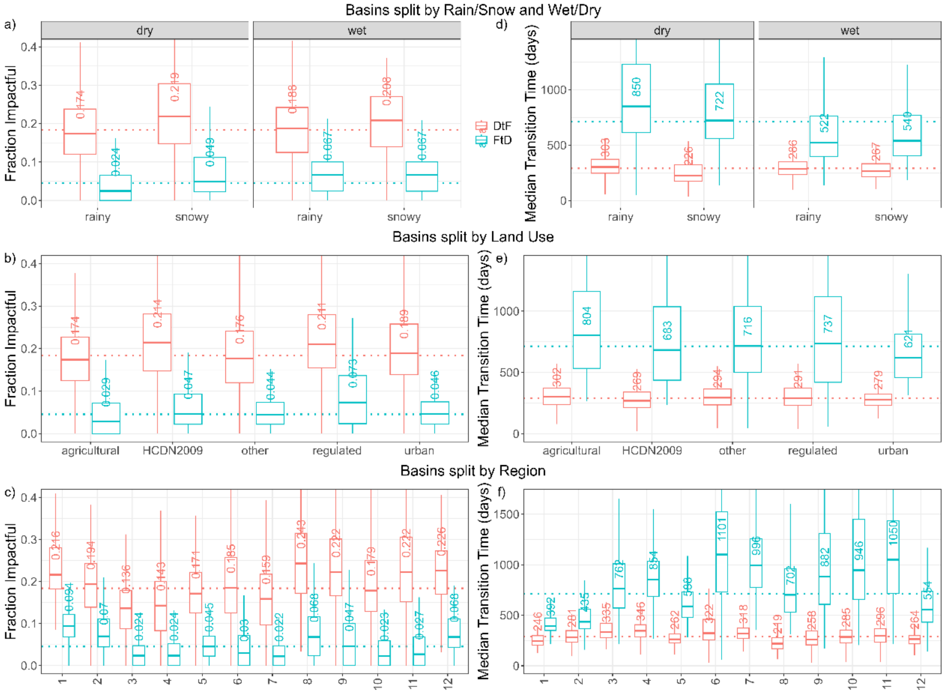

Figure 6: Box plots showing the fraction of transitions (a, b, c) that are impactful and the median transition time between events (d, e, f) for a variety of different basin classifications. **(a, d)** Basins split by rain/snow and wet/dry partitions. **(b, e)** Basins split by land use type. **(c, f)** Basins split by flow region. For each box plot, the center line indicates the median and the box boundaries represent the interquartile range (IQR). Whiskers extend to the furthest data point within 1.5 times the IQR from the box boundaries; individual outliers falling outside this range are omitted from the display for visual clarity. Horizontal dotted lines indicate the global median values for drought-to-flood (DtF; red) and flood-to-drought (FtD; blue) transitions. Refer to Fig. S4 for a map of regional clusters, with names and numbers.

3.4 Decoupling of Meteorological and Hydrological Whiplash

A central finding of this study is that hydrological whiplash rarely coincides with meteorological whiplash, revealing substantial watershed filtering of climate signals. Fig. 7 (a, b, e, f) shows the co-occurrences of hydrological and meteorological sub-seasonal transitions. The fraction of whiplash events that have a corresponding meteorological/hydrological transition within one season is generally small; 24.0% of DtF transitions (n=15393) have a dry-to-wet transition within one season, which is the highest

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fraction of agreement. This is followed by FtD transitions (18.5% have a co-occurring wet-to-dry transition, n=7018), then dry-to-wet climatic transitions (13.3%, n=32117). Wet-to-dry transitions (n=34808) have the lowest rates of overlap with just 4.1% co-occurring with an FtD transition. This asymmetric decoupling, where dry-to-wet meteorological transitions are more likely to produce DtF streamflow transitions (13.3%) than wet-to-dry transitions are to produce FtD transitions (4.1%), indicates direction-specific controls related to basin storage and antecedent conditions (Berghuijs et al., 2016; Wasko et al., 2020; Nanditha et al., 2022; Matanó et al., 2024).

We find that there is a greater coincidence between dry-to-wet and DtF than wet-to-dry and FtD. DtF hydrological transitions most commonly co-occur with a dry-to-wet transition in the South Central region (a median of 40%), followed by the Central Forests (33%; Fig. S9a). Many regions have high variability across streamgages in the co-occurrence between DtF and dry-to-wet transitions, with the Southern Mid-Atlantic and Southeast regions having a 75th percentile (Q75) co-occurrence of 50% and a Q25 of 0%. There is high variability in the co-occurrence of FtD transitions and wet-to-dry transitions (Fig. S9b). All regions except the Central Plains, Southwest, and South Central have median values of co-occurrence of zero, but many regions have streamgages with high frequency of overlap (Q75 ≥ 50% in Southern Mid-Atlantic, Central Forests, Central Plains, and South Central regions).

When sub-seasonal meteorological transitions occur, they are much less likely to co-occur with a hydrological sub-seasonal transition (Fig. S9e, f). It is important to note that the co-occurrence of these transitions is sensitive to transition definitions, the fraction of spatial overlap required for a basin (e.g., did a meteorological transition occur over 10 or over 50% of a basin area), how meteorological and hydrological transitions are aligned, and the numbers of each type of transition event (Table S1). At low overlap thresholds (e.g., 0.1), a larger share of hydrological transitions register overlap with a meteorological transition, but tightening the overlap requirement to 0.5 or higher reduces these percentages by roughly half. This highlights that many apparent co-occurrences arise from only partial spatial alignment rather than full watershed coverage. This pattern demonstrates that hydrologic–meteorologic extreme transition synchrony is uncommon across overlap thresholds, but the precise numerical co-occurrence rates depend strongly on how spatial overlap is defined.

For dry-to-wet transitions, the most frequent co-occurrence is in the Central Forests (median of 17%). Wet-to-dry transitions are even less likely to have a nearby FtD transition, and only 2 of the 12 regions have a Q75 ≥ 10% (Northeast region=12%, Southwest region=11%).

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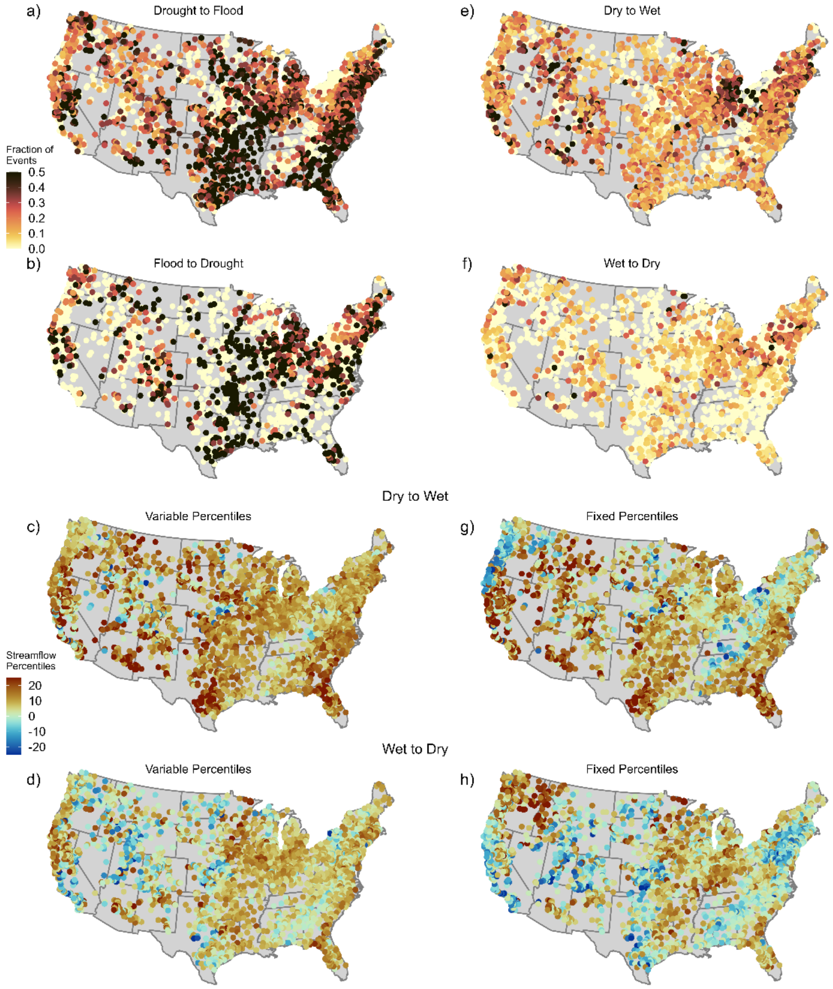

Figure 7: Comparisons of occurrence between meteorological and hydrological transitions. Top two rows are the fraction of transitions that have a corresponding transition in the related system within one season, e.g., the fraction of drought-to-flood transitions that have a dry-to-wet meteorological transition within one season. Panels c, d, g, and h show the maximum changes in the variable and fixed streamflow percentiles during the season of the transition and 90 preceding days relative to the median percentile changes during all periods. Browner colors show a more extreme change than normal, while bluer colors show a smaller change in percentiles.

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Figure 7 (c, d, g, h) shows how streamflow percentiles change during meteorological sub-seasonal transitions. During the periods surrounding meteorological sub-seasonal transitions from wet-to-dry (relative variable percentile change = 6.3, relative fixed percentile change = 2.5) and dry-to-wet (10.9 and 7.7), the maximum streamflow percentiles changes are larger than during average periods; however, these changes are substantially smaller (9.4-12.9%) than the changes that occur during FtD (18.7 and 14.9) and DtF (20.3 and 20.6) sub-seasonal transitions (Fig. S10, Fig. S11).

For dry-to-wet meteorological transitions, streamflow percentile changes relative to normal are highest for variable percentiles in the Southwest (16%) and South Central (14.3%) regions and for fixed percentiles in the Southwest (13.4%), Rocky Mountains (12.1%), and California and Interior West (12.1%) regions (Fig. S9c, g). Streamflow percentiles change the least during dry-to-wet meteorological transitions in the Northwest region (relative variable change = 7.9% and relative fixed change = -1.9%). Certain parts of the Appalachian Mountains also have relatively small fixed-percentile changes (Fig. 7g).

Across many streamgages, particularly in the California and Interior West (-2.6% relative to the average change of all periods), Rocky Mountains (-0.8%), and Northern Mid-Atlantic (-0.5%) regions, streamflow percentiles (fixed) during periods of wet-to-dry meteorological transitions change less than the average changes across all periods (Fig. S9h). Interestingly, across parts of northwestern and southeastern CONUS, fixed percentiles change less during FtD transitions than during average periods (Fig. S10d). In northwestern CONUS in particular, many streamgages seem to have much larger fixed percentile transitions during wet-to-dry transitions than during FtD transitions, which is not the case across most of CONUS (Fig. 7h vs Fig. S10d).

Figure S12 shows that the maximum streamflow percentile changes associated with meteorological wet-to-dry transitions are only slightly higher than those during seasons with no meteorological transitions. To evaluate these patterns, we identified wet-to-dry and dry-to-wet periods using the seasonal meteorological transition catalog of Swain et al. (2025), and for each period computed the maximum change in streamflow percentiles (fixed and variable) within the transition season and the preceding 90 days. Although both wet-to-dry and dry-to-wet seasons exhibit higher maximum streamflow percentiles than periods with no transition, wet-to-dry periods generally do not reach streamflow percentiles low enough to qualify as hydrological droughts, which likely explains the weak alignment between meteorological wet-to-dry events and hydrological FtD transitions (Fig. 6f).

4 Discussion

4.1 Patterns of Hydrological Whiplash Occurrence

Across all analyses, DtF transitions emerge as fundamentally more frequent, faster, and spatially coherent than FtD transitions, indicating a persistent asymmetry in watershed response to hydroclimatic extremes. The largest fractions of DtF transitions are under 30 days in duration for northeastern CONUS, parts of the West, and along the P/PET ≈ 1 line from North Dakota down to Texas. Short-term DtF transitions that we see in the Northwest and southern California (Fig. 3 a, b) have been highlighted in prior studies similarly showing abrupt drought endings in the West often linked to atmospheric rivers (Dettinger, 2013; Swain et al., 2018; White et al., 2019). Previous studies show rapid termination of droughts in the East due to tropical cyclones, which can terminate up to 41% of droughts in southeastern CONUS (Kam et al., 2013; Maxwell et al., 2012, 2013). While we do not find that southeastern CONUS has frequent sub-seasonal transitions (Fig. 3 a, b) from DtF, this could be due to differences in meteorological versus hydrological transitions, other differences in definitions, or because the frequency of these transitions does not necessarily indicate their impact, or the relatively weak hydroclimatic seasonality in the region, where the absence of a pronounced dry season leads to fewer identified drought events. This spatial pattern of short-term transition hotspots is robust across multiple drought and flood definitions, as shown in Fig. 5, where the Northeast and Northwest regions, and along the P/PET ≈ 1 line consistently exhibit the highest fractions of short-term DtF transitions regardless of threshold choice; however, there are regions like the Rocky Mountains that are more sensitive to event definitions.

Few FtD transitions occur in under 30 days, and FtD transitions lasting less than 90 days are focused in the Northeast, Northwest, Northern Mid-Atlantic, and Rocky Mountains regions, while Southeast, southern mid-Atlantic, Central Plains, California and Interior West, and South Central regions generally show fewer sub-seasonal transitions. Although few FtD transitions occur within 30 days, those that do occur often coincide with large percentile declines and extended recovery periods (Fig. 6, Fig. S10), making them disproportionately impactful for water management.

Globally, He and Sheffield (2020) found that ~11% of droughts are followed by pluvials the next season, which is much higher than the 4.1% of droughts that we find are followed by floods within 90 days, highlighting the broad-scale importance of definition choice in detecting transitions. We demonstrate that the patterns and characteristics of hydrological whiplash events are sensitive to the methodological choices in defining drought events, flood events, and their transitions, confirming findings from Anderson et al. (2025). Figure 4

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illustrates how transition counts vary by orders of magnitude depending on the chosen drought and flood thresholds, yet the fraction of short-term transitions (<30 days) consistently favors DtF over FtD transitions across most methods, demonstrating the robustness of this asymmetry. Figure 5 further demonstrates that short-term DtF transitions are far more prevalent and spatially extensive than FtD transitions across all drought and flood definitions tested, particularly across the eastern and central United States. More lenient drought and flood definitions result in increasing frequencies of short-term transitions (Fig. 5).

Additionally, differing definitions have differing impacts between regions. Using a fixed 99th percentile threshold for floods rather than a once a year peaks over threshold method increases the national fraction of sub-seasonal DtF transitions (Fig. 4) but dramatically reduces the frequency of transitions in the Rocky Mountains and California and Interior West regions. Because of the typically long snowmelt driven flood peaks in this region, using a fixed 99th percentile threshold for floods decreases the number of floods in this region even while increasing the average number of floods nationally, resulting in fewer short-term and sub-seasonal transitions in that region even as the average number of national transitions increases. We discuss further methodological choices and sensitivities at length in the supplement section “Methodological Considerations and Sensitivity.”

Despite regional sensitivity to specific thresholds, the overall asymmetry between DtF and FtD transitions is robust. Across all tested definitions (Fig. 5), lenient definitions generally increase the fraction of short-term transitions, while stricter definitions reduce counts, but the broad spatial patterns remain consistent. This indicates that our finding of more frequent, more rapid, and more spatially extensive DtF transitions compared to FtD transitions is not an artifact of a single methodological choice but rather demonstrates fundamental differences in hydrological processes governing the two transition types. The consistent asymmetry between DtF and FtD transitions may may be due to watershed storage that fills rapidly but depletes slowly, producing faster wetting responses and more prolonged drying recoveries.

Comparing to recent studies, Götte and Brunner (2024) focused exclusively on DtF transitions and demonstrated strong controls from snowmelt and reservoir regulation on transition timing and frequency. Our results are consistent with their finding that DtF transitions are generally faster than their reverse; however, by explicitly analyzing FtD transitions, we show that the two directions differ not only in speed but also in seasonality, spatial clustering, and sensitivity to watershed disturbance. Yang et al. (2025) similarly document asymmetry between DtF and FtD transitions using long-term discharge records and highlight the modulating role of human regulation. Our findings complement this work

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by demonstrating that, even where long-term trends differ, impactful transitions disproportionately occur in the drought-to-flood direction, particularly in rain-dominated and urbanized basins.

4.2 Human impacts on hydrological extreme transitions

Human modifications amplify the asymmetry between DtF and FtD transitions in different ways: urbanization accelerates both wetting and drying responses by reducing subsurface and hyporheic storage and shortening catchment response times, while regulation generally elongates transitions. Across all land uses, DtF transitions are consistently faster and more frequent than FtD transitions, reinforcing a directional asymmetry in watershed response to hydroclimatic extremes (Fig. 6). Urban basins exhibit the fastest FtD and second-fastest DtF transition times and among the highest fractions of sub-seasonal transitions, likely resulting from impervious surfaces that accelerate runoff. Agricultural basins, by contrast, had lengthened transition times—especially for FtD— and less frequent sub-seasonal transitions. Although land-use characteristics modulate transition behavior, climate controls exert stronger influence because differences among regulated, urban, agricultural, and reference basins are slightly smaller than those between rain/snow and wet/dry regimes. Snow-dominated systems are far more prone to sub-seasonal DtF transitions than rain-dominated systems, with the most pronounced differences in dry snow-fed basins. Overall, impactful transitions occur more often for DtF transitions across nearly all basin types, while FtD transitions show greater variability and sensitivity to regulation and regional climate.

Individual examples illustrate diverse pathways through which human modifications influence transition dynamics. The Bill Williams River case (Fig. 2f) exemplifies direct reservoir control effects, where Alamo Dam operations created a complex sequence of transitions during 1992–1993, with event identification highly sensitive to threshold choice precisely because dam releases can maintain flows near threshold boundaries for extended periods. Urban modifications similarly alter transition characteristics, as observed in Huge Creek (Fig. 2c), where rapid drainage and reduced storage capacity produce consistently fast FtD transitions across multiple definition sets. Even in less directly managed systems, human activities shape vulnerability: the 2025 Guadalupe River DtF transition in Texas (Fig. 2b) resulted in multiple fatalities (NOAA, 2025). This event underscores how rapid hydrological shifts interact with human settlement patterns and emergency communication and response capacity to determine ultimate impacts to life and property.

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Several studies show that specific water management choices—such as irrigation withdrawals, levee construction, and reservoir operating rules—can alter how quickly basins transition between wet and dry states (He et al., 2017; Holden and Shiferaw, 2004; Di Baldassarre et al., 2017). Rather than restating their general impacts, we refer to these examples here to illustrate how human systems can differentially speed or delay wetting versus drying, reinforcing the directional asymmetries observed in our DtF and FtD transition patterns.

Our results show that different basin types have different fast transition risks; however, these influences are complex amongst a variety of different basin characteristics impacting hydrological whiplash. Quick DtF transitions compress the window for reservoir refill, flood-control operations, and water-quality protection, while FtD transitions can undermine post-flood recovery, and exacerbate warm-season water stress. These asymmetric risks are not captured by annual or meteorological metrics alone, underscoring the need for hydrologically based indicators when assessing compound-extreme impacts on water systems.

4.3 Hydrological whiplash and meteorological whiplash

While hydroclimatic whiplash identified from precipitation or water-balance indices is projected to intensify under warming (Li et al., 2025; Maharjan et al., 2025), our results show that hydrological whiplash rarely coincides with meteorological whiplash. There is greater coincidence between dry-to-wet and DtF (13.3%) than wet-to-dry and FtD (just 4.1%), although both are infrequent. The particular lack of FtD events occurring with wet-to-dry meteorological events is likely because streamflow percentiles often do not get dry enough to be identified as streamflow droughts (Fig. S12), even when these meteorological events drive declines in streamflow (Fig. S9). This issue disproportionately affects FtD transitions because hydrological drought requires sustained low flows, whereas floods in the DtF direction can occur rapidly in response to single events.

This partial alignment indicates the role of basin storage, snowpack, and regulation in buffering streamflow responses and differences in definitions between meteorological and hydrological extremes. Prior work indicates that meteorological whiplash has already increased with warming and is projected to intensify (Swain et al., 2025), but hydrological whiplash often diverges due to watershed processes. These patterns reflect the influence of region-specific climate drivers and watershed storage dynamics which help explain why the degree of overlap between meteorological and hydrological transitions varies across CONUS. Because sub-seasonal hydrological transitions frequently occur without

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corresponding meteorological whiplash, predictability based solely on hydroclimate indicators may be lowest precisely during periods of highest operational risk.

Storage regimes play a critical role in mediating hydrological extreme transitions. Declining reservoir capacity due to sedimentation and increasing consumptive demands have reduced the ability of storage infrastructure to buffer extreme transitions, with global reservoir construction yielding diminishing returns in terms of downstream flow regulation (Li et al., 2023). Groundwater storage depletion similarly weakens drought buffering capacity, potentially intensifying the speed and magnitude of transitions (Bierkens and Wada, 2019). In snow-dominated systems, declining snowpack storage under warming reduces the natural buffering that moderates seasonal flow transitions, accelerating the shift from snowmelt-sustained baseflows to precipitation-driven intermittency (Musselman et al., 2021). Soil moisture storage dynamics introduce additional complexity; antecedent drought conditions can either amplify flood responses through reduced infiltration capacity in severely degraded soils or suppress them through increased soil moisture deficits that absorb initial precipitation (Wasko et al., 2020; Berghuijs et al., 2016). These storage-mediated feedbacks indicate that understanding transition dynamics requires explicit consideration of how different storage components—surface, subsurface, and natural—interact to either dampen or amplify climate forcing across multiple timescales (Ward et al., 2020; Mazzoleni et al., 2021).

4.4 Differences between DtF and FtD transitions

Case studies reveal distinct process differences between DtF and FtD transitions (Fig. 2). More urban systems like Huge Creek demonstrate relatively consistent FtD transition times (12-15 days) regardless of definition, suggesting that urban drainage infrastructure and impervious surfaces create predictable recession patterns (Fig. 2c). In contrast, snow-dominated systems like the Fish River in Maine exhibit high sensitivity to definition choice for DtF transitions, where early spring snowmelt floods transition into summer droughts with timing heavily dependent on how low flows are characterized (Fig. 2d). Regulated systems add another layer of complexity: the Bill Williams River below Alamo Dam in Arizona experienced seven quick transitions during 1992–1993 under lenient definitions but only three under strict criteria (Fig. 2f), illustrating how reservoir operations can create frequent oscillations between flow conditions that may or may not meet extreme event thresholds depending on methodological choices. Furthermore, over the course of our study period, ecological flows were implemented on the Bill Williams River and represented a substantial change in reservoir release operations that impact DtF and FtD classifications on this river (Shafroth and Beauchamp, 2006; Hickey et al., 2016; Konrad, 2010).

DtF transitions occur more quickly than FtD transitions. Sub-seasonal transitions in both directions are most common from February to April, indicating seasonal precipitation and watershed storage drivers. Rare but dramatic whiplash events exist—such as the July 2025 Texas event (Fig. 2b) that shifted from drought (<1st percentile flow) to flood (>99th percentile) in just one day. Out of ~92,000 transitions, only ~0.1% show such extreme single-day shifts.

Described case studies align with other historical examples, such as California's 2016–2017 flood that abruptly ended the 2013–2015 drought (Wang et al., 2017; White et al., 2019; Swain et al., 2018), and with broader projections that compound extremes may intensify with continued warming (Stevenson et al., 2022; Swain et al., 2025).

When assessing the change in streamflow magnitude during different types of transitions, several key patterns emerge (Fig. S11). Across transition types, DtF and dry-to-wet transitions exhibit the greatest consistency in their streamflow percentile responses, whereas fixed-percentile changes show particularly weak correspondence between FtD and WtD transitions. This contrast seems to be driven by the fact that meteorological wet-to-dry transitions often produce little to no detectable change in streamflow percentiles relative to periods with no identified transitions, indicating that a larger fraction of WtD meteorological shifts do not substantially perturb watershed-scale hydrologic conditions.

4.5 Scientific Uncertainties and Challenges

While this study and prior work (Götte and Brunner 2024; Matanó et al. 2024) have characterized the spatiotemporal variability of drought–flood transitions, further research is needed to assess how their frequency, duration, and severity are changing and how projected shifts may affect water management. Observed transitions can be driven by atmospheric rivers, hurricanes, teleconnection patterns, and antecedent conditions, yet meteorological whiplash does not always translate into hydrological whiplash because basin storage, regulation, and other watershed characteristics can buffer or delay streamflow responses.

By testing multiple drought and flood definitions through a sensitivity analysis, this study reduces methodological ambiguity and provides a more robust framework for testing hypotheses about hydrological extreme transitions across large watershed samples

(Anderson et al., 2025). Robust detection of transition timing and sequencing enables clearer evaluation of whether declining baseflow persistence is associated with faster and more extreme DtF transitions, whether antecedent drought amplifies or suppresses floods depending on storage regime (Wasko et al., 2020; Berghuijs et al., 2016), and whether transition speed is changing independently of flood or drought magnitude. The same framework strengthens tests of post-drought recovery, including slowing recovery, hysteresis, and increasing recovery asymmetry under future climates (Parry et al., 2016), and facilitates detection of nonlinear responses associated with storage loss and precipitation intensification (Ward et al., 2020). Consistent transition detection across stream orders further enables rigorous comparison of headwater and mainstem rivers in terms of coupling strength and early emergence of extreme behavior (Brunner et al., 2021).

A remaining challenge is explicitly quantifying how antecedent storage conditions and storage dynamics during transitions control their speed, magnitude, and predictability. Antecedent soil moisture strongly governs runoff efficiency, with wet conditions producing rapid, efficient runoff generation and dry conditions either suppressing floods or triggering nonlinear responses once thresholds are exceeded (Merz and Blöschl, 2009; Penna et al., 2011). Groundwater depletion during droughts similarly alters recession characteristics and recovery timescales (Troch et al., 2013), potentially explaining the observed asymmetry between faster DtF and slower FtD transitions. Future work could quantify how soil and groundwater storage filling and depletion modulate transition rates, particularly under declining storage capacity associated with climate and land-use change.

Equally important is understanding when extreme transitions propagate through reservoir systems versus when dams decouple downstream hydrology from upstream signals. Although reservoirs are often assumed to dampen variability (Poff et al., 2007), buffering capacity depends on antecedent storage, operating objectives, and inflow magnitude relative to storage capacity (Di Baldassarre et al., 2017), and reservoirs may just shift drought deficits in time rather than mitigating them (Van Loon et al., 2022). Recent work suggests reservoir impacts on extremes exhibit threshold behavior, with buffering capacity degrading rapidly once storage falls below critical levels (Brunner et al., 2023). Systematic evaluation of how transition type, operating rules, and antecedent conditions interact will be essential for understanding downstream vulnerability to fast hydrological transitions.

Conclusions

Our CONUS-wide analysis highlights the characteristics of fast transitions between hydrological extremes, how these transitions vary regionally and across basins with different characteristics, which areas and types of watersheds may experience the most impactful transitions, and how these transitions are connected to sub-seasonal transitions between meteorological extremes. We find that DtF transitions occur more quickly and are most common in northeastern and northwestern CONUS, southern California, the Rocky Mountains, and along the P/PET ≈ 1 line from North Dakota down to Texas, highlighting regions of increased concern of the risk of hydrological whiplash. This, paired with findings that snow-dominated or urban, regulated, or minimally altered watersheds have the most frequent sub-seasonal DtF transitions, identifies potential regions of elevated risk for hydrological whiplash. Although less frequent than DtF transitions, we find that FtD transitions can involve large and rapid declines in streamflow percentiles and may warrant increased attention in future research given distinct water management challenges.

Modest coincidence between hydrological and meteorological whiplash found in our study shows the importance of accounting for the roles that watershed characteristics like soil water storage, snowpack, and regulation play in mediating how climatic signals drive streamflow. Additionally, our findings demonstrate the importance of careful choices in methodological event definitions, which can have large impacts in the characterization of extreme events and their transitions, both within and between systems.

This study is an incremental step in understanding the dynamics of hydrological whiplash; however, much future work is still needed. Further work could evaluate how hydrological whiplash events have changed historically and predict how they will change in the future, determine how antecedent storage conditions and storage dynamics during transitions control their speed, magnitude, and predictability; determine under what circumstances extreme transitions propagate through reservoir systems versus situations where dams effectively capture or overwrite upstream signals; and assess the socioeconomic and ecological impacts of impactful hydrological whiplash events.

Author Contributions

CES and JCH conceptualized the study and contributed equally to data curation. CES led the methodology, investigation, formal analysis, and visualization. JCH led project administration and provided resources, while also assisting with methodology, investigation, and formal analysis. Both authors contributed equally to the original draft and subsequent revisions.

Disclaimer

This information product has been peer reviewed and approved for publication as a preprint by the U.S. Geological Survey. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government. This research employed generative AI (Microsoft 365 Copilot Chat and Gemini 3.1 Pro) for manuscript editing and code troubleshooting. All AI-generated outputs, including text, and code, were reviewed, validated, and, where necessary, modified by the authors to ensure scientific rigor, integrity, accuracy, and compliance with USGS standards.

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Code and data availability

All code and data used in this study is publicly available from the USGS ScienceBase repository (Simeone and Hammond, 2026)

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