

## **Supplement for “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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### **Text S1: Methodological Considerations and Sensitivity**

The choice between fixed and variable percentile thresholds for drought identification represents a fundamental methodological decision with substantial implications for transition detection. Both approaches have their own strengths and applications; however, variable percentile methods (such as the 10th percentile used in this study) are particularly suited for characterizing hydrological extremes across diverse seasonal flow regimes. Fixed percentile thresholds, which compare flows to the full period of record regardless of season, can systematically fail to identify ecologically or operationally relevant low flows during naturally low-flow seasons while inappropriately flagging moderate flows as droughts during high-flow seasons. This seasonal limitation is particularly problematic in snow-dominated systems, where spring snowmelt produces consistently high flows that would rarely fall below a fixed annual threshold, and in Mediterranean climates with distinct wet and dry seasons. Variable percentile methods address this by comparing flows to expected conditions for that specific time of year, enabling detection of hydrologically meaningful departures from normal conditions across all seasons. For completeness, we include analysis using fixed percentile drought definitions in the supplemental information, which demonstrate that while absolute event counts differ, the spatial patterns and directional asymmetry between drought-to-flood (DtF) and flood-to-drought (FtD) transitions remain consistent.

The application of a 7-day moving average to streamflow data before drought identification similarly represents a balance between noise reduction and event detection sensitivity.

Daily streamflow exhibits substantial short-term variability driven by individual precipitation events, diurnal cycles, and measurement noise, which can lead to spurious drought initiation and termination if applied directly to daily values. The 7-day window smooths this high-frequency variability while preserving the signature of persistent low-flow conditions. However, this averaging introduces a temporal offset that affects the precise timing of drought onset and termination by approximately 3-4 days, which could influence the classification of very short transitions (e.g., distinguishing 14-day from 18-day events). An alternative approach of maintaining daily streamflow throughout the analysis would provide temporal consistency but at the cost of increased noise in drought identification. Our transition thresholds ( $\leq 14$  days,  $\leq 30$  days,  $\leq 90$  days) were defined based on the smoothed 7-day flows, and the transition period is measured from the end of the drought event to the start of the flood event rather than being dependent on drought or flood duration. The 7-day window was selected to incorporate more seasonally relevant observations and to provide a denser empirical basis for percentile estimation, which reduces step-like behavior in the empirical cumulative distribution function and yields a smoother, more continuous percentile time series. The 7-day window was selected over a 30-day window percentile which can deviate from a stable distribution in certain times of the year at certain streamgages. For example, a 30-day window implemented at a streamgage that has a large and consistent seasonal change (e.g., a consistent snowmelt peak) can result in streamflow percentiles around that peak being unstable from day to day, e.g., the stream is below the 20<sup>th</sup> percentile either much more or much less than 20% of days on a given calendar date.

Our flood identification using a peaks-over-threshold approach calibrated to yield approximately one event per year represents a middle ground between overly restrictive and overly permissive flood definitions. This choice aligns with two widely used flood characterization methods: annual maximum flow analysis (which by definition produces one event per year) and peaks-over-threshold approaches where the threshold is commonly set to achieve a target event frequency. The one-per-year criterion balances the need to capture operationally significant high flows against the risk of identifying numerous minor peaks that would not be considered floods in practice. Alternative flood definitions—including fixed percentiles (e.g., 99<sup>th</sup> or 99.5<sup>th</sup>), multiple return periods (e.g., 2-year, 5-year, 10-year floods), or stage-based thresholds (e.g., bankfull flow)—could be applied depending on the specific application. Our sensitivity analysis demonstrates that while absolute transition frequencies vary substantially across flood definitions, the fundamental pattern of more frequent and quicker DtF transitions compared to FtD transitions persists across all tested definitions.

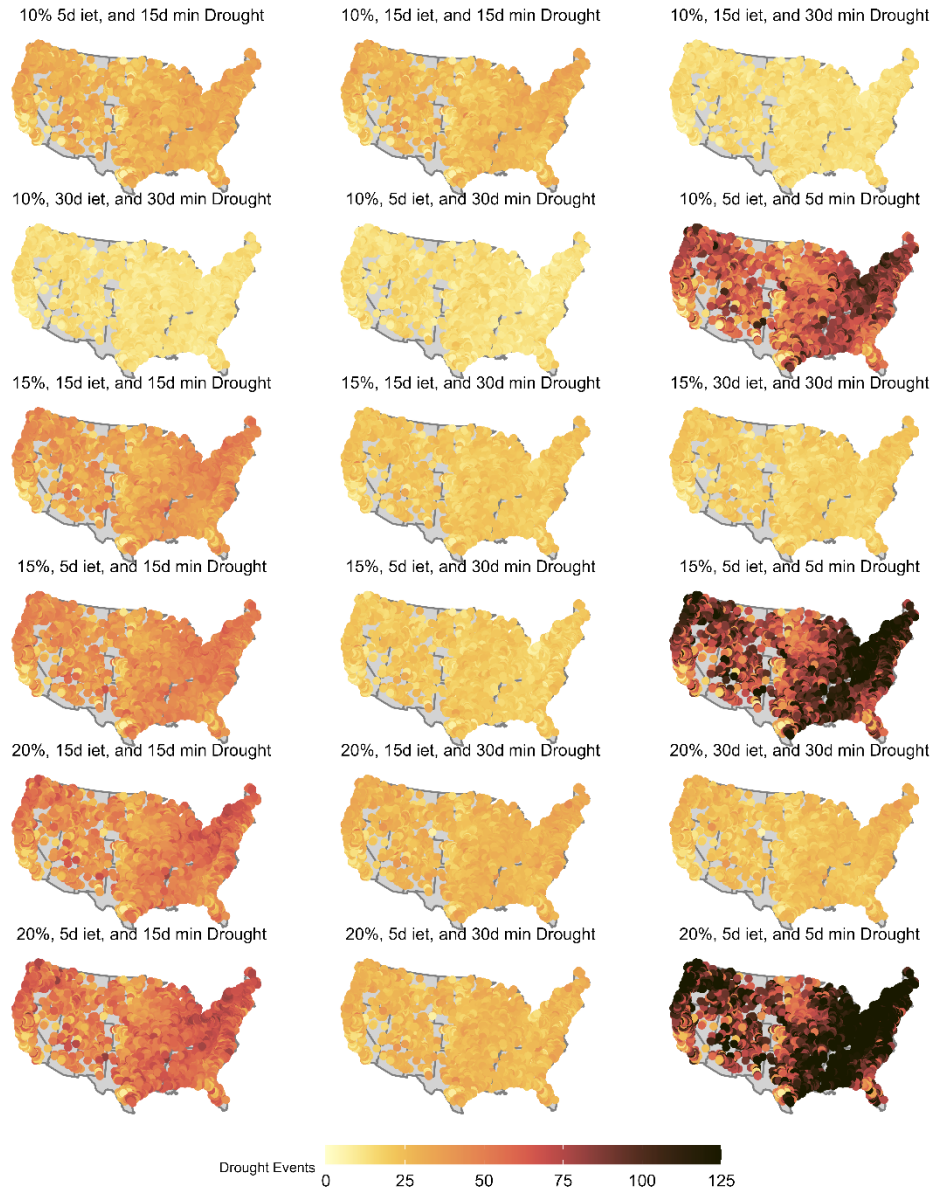
The transition timescales examined in this study ( $\leq 14$  days,  $\leq 30$  days,  $\leq 90$  days) encompass quick hydrological shifts comparable to those documented in the flash drought literature, though the mechanisms and indicators differ. Flash drought onset, defined as rapid intensification of drought conditions, exhibits considerable definitional variability across studies, with proposed onset timescales ranging from 5 days to 8 weeks (Lisonbee et al., 2021). Our 14-day rapid transition threshold falls within this range and captures events where streamflow shifts from flood to drought conditions within approximately two weeks, representing hydrologically extreme volatility. The 30-day short-term transition threshold aligns with commonly used sub-seasonal timescales in both flash drought and precipitation whiplash research, while the 90-day sub-seasonal threshold provides broader context for understanding the full spectrum of rapid to moderate-speed transitions. The absence of a universally accepted definition for rapid hydrological transitions—analogueous to the ongoing debate surrounding flash drought definitions—necessitates transparent reporting of methodological choices and systematic sensitivity analysis across multiple threshold combinations, as demonstrated in this study.

The case studies presented in **Error! Reference source not found.** illustrate how methodological choices shape event identification in practice. For example, Hurricane Irene's impact on the Androscoggin River in Maine (2011) demonstrates a rapid DtF transition where lenient definitions identify a 2-day transition while stricter definitions extend this to 20 days (**Error! Reference source not found.a**). The 2025 Guadalupe River event in Texas exemplifies an extremely rapid transition (1 day) that is consistently identified across all definitions due to its severity, transitioning from 2.3 to 12.8 feet of stage in a single day. In contrast, the 2012 flash drought on the Caney River in Kansas (**Error! Reference source not found.e**) shows substantial sensitivity to drought definition choice, with study definitions ending the drought on April 30 but strict definitions not identifying drought termination until June 16—a difference of 47 days that fundamentally alters the characterization of recovery timing. These examples underscore that while the most extreme events are robust to definitional choices, moderate events near threshold boundaries can be classified quite differently depending on the selected criteria, reinforcing the importance of the sensitivity analyses presented in this study.

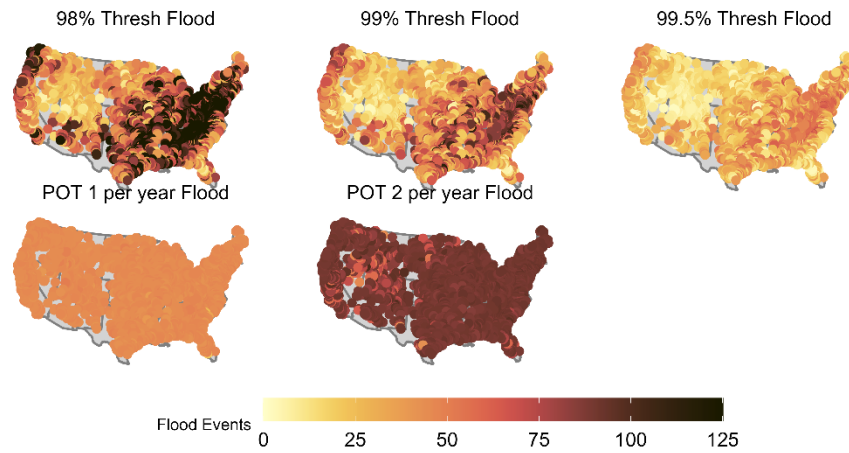
Adding a fixed percentile shift requirement to confirm that transition events are impactful reduces the fraction of short transitions. This requirement primarily influences the FtD and DtF fractions in the Rocky Mountains region which has many highly seasonal snowmelt dominated basins (Figure S14).

Transition Type	Overlap Fraction	Transitions	% Transitions Within Same Season	% Transitions Within the same or Adjacent Season
DtF	0.1	15393	14.8	24.0
DtF	0.25	15393	12.4	19.9
DtF	0.5	15393	9.8	15.2
DtF	0.75	15393	7.5	11.5
DtF	0.99	15393	5.2	8.0
DtW	0.1	32117	7.1	13.3
DtW	0.25	25552	7.5	13.8
DtW	0.5	18700	8.0	14.5
DtW	0.75	13696	8.5	15.1
DtW	0.99	8685	9.3	16.6
FtD	0.1	7018	12.2	18.5
FtD	0.25	7018	10.1	15.4
FtD	0.5	7018	7.6	11.7
FtD	0.75	7018	6.1	9.1
FtD	0.99	7018	4.1	6.3
WtD	0.1	34808	2.5	4.1
WtD	0.25	28413	2.5	4.1
WtD	0.5	21366	2.5	4.1
WtD	0.75	15988	2.7	4.3
WtD	0.99	10312	2.8	4.5

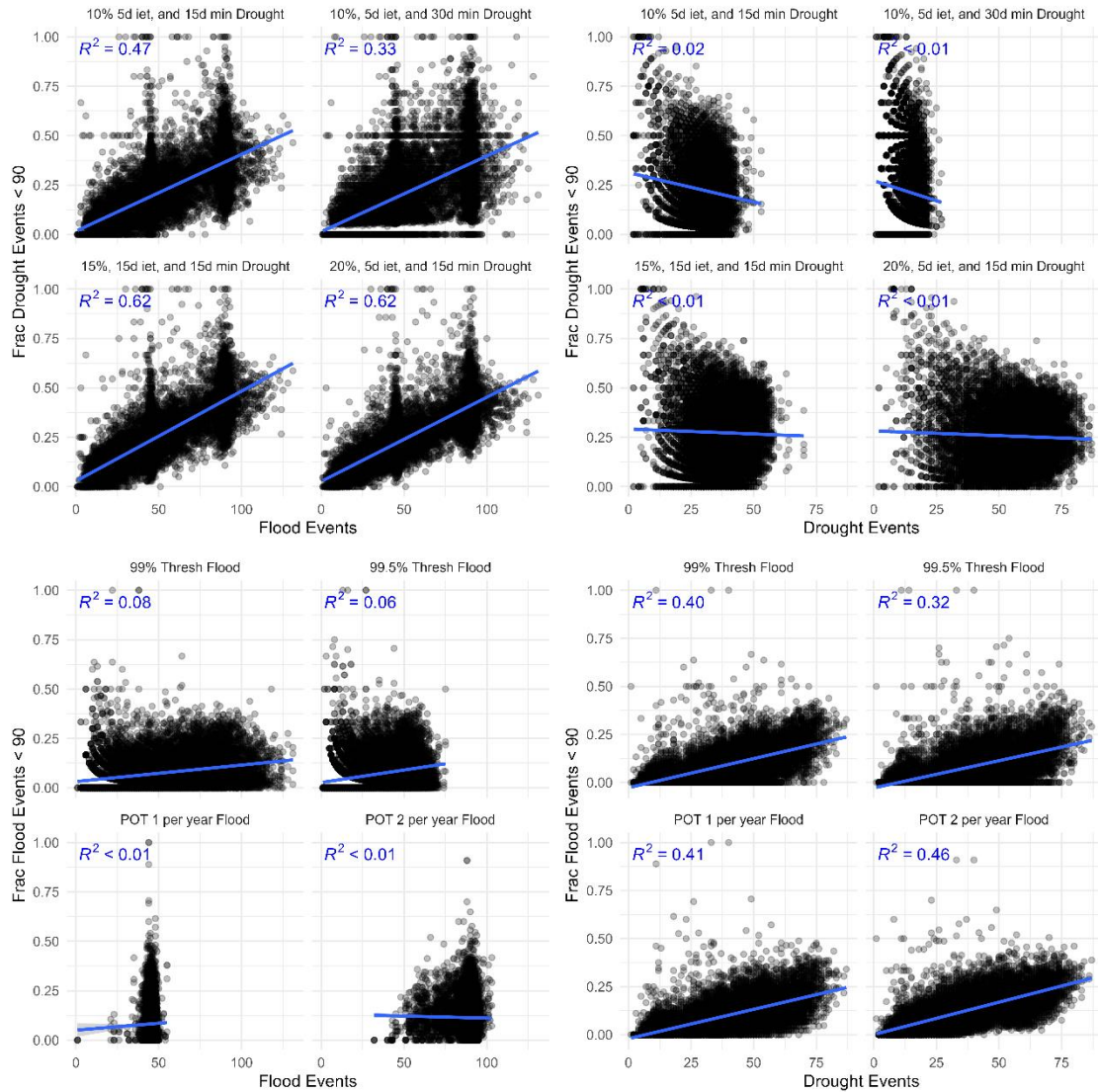
**Table S1:** Table showing the percentage of hydrological and meteorological transitions that have a corresponding transition either in the same season or within one season in either direction for several different levels of meteorological overlap with each hydrologic basin. Overlap fraction indicates the fraction of the watershed that raster pixels with active meteorological extreme transitions overlapped with a watershed experiencing a hydrological extreme transition. An overlap fraction of 0.5 indicates that at least half of the pixels overlapping with the watershed had an active meteorological extreme transition. Hydrological extreme transitions are for the definition focused on in the main text: 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.



**Figure S1:** Total number of drought events using several different methods. We identify drought events at each site across this period using 18 different drought definitions derived from the parameter combinations described below. We use 3 different drought percentile thresholds (10, 15, and 20), 3 different inter-event duration values (5, 15, and 30 days) and 3 different minimum drought durations (5, 15, and 30 days); however, we do not allow the minimum drought durations to be less than the inter-event duration values.

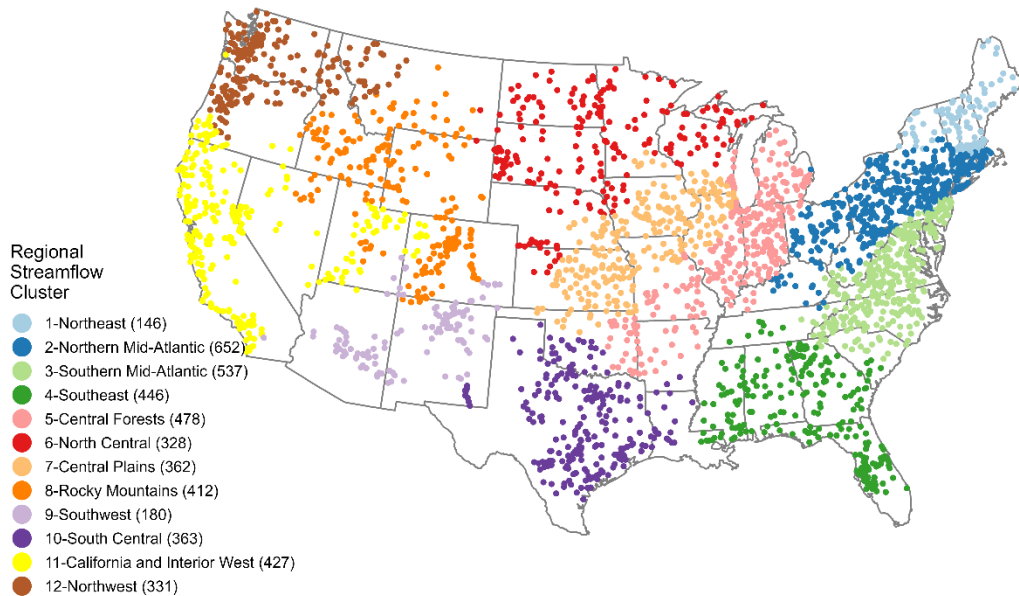


**Figure S2:** Total number of flood events using several different methods. We identify flood events at each site using 5 different food definitions; three fixed percentile thresholds of 98, 99, and 99.5; and two peaks-over-threshold methods identifying an average of 1 or 2 floods per year.

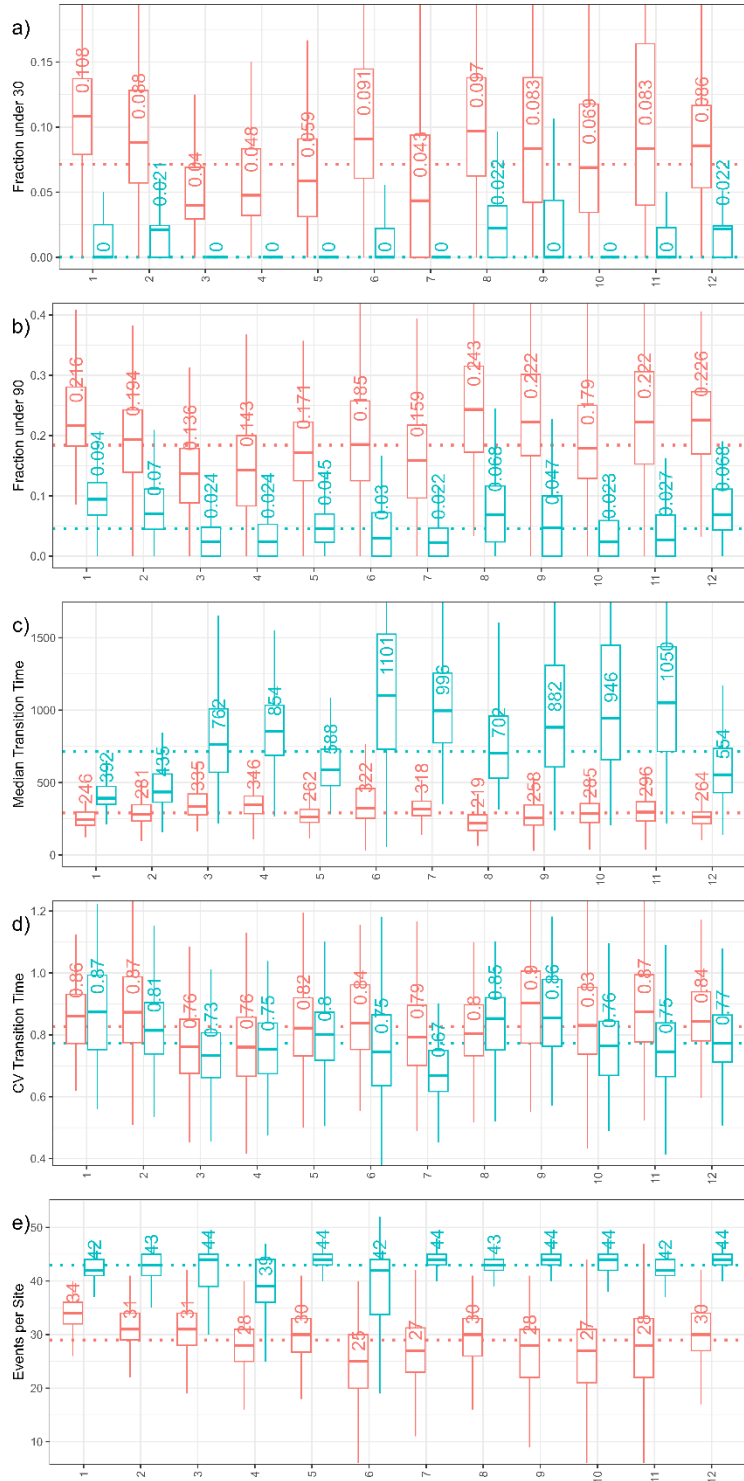


**Figure S3:** Scatter plots of the fraction of drought (top) or flood (bottom) transitions quicker than 90 days vs the total number of flood (left) or drought (right) events at that site for 4 different identification methods. This figure illustrates the necessity of employing event identification methods that yield relatively balanced frequencies of flood and drought events and exhibit spatially homogeneous detection rates across the conterminous United States. When event detection methods produce highly disparate event counts or spatially heterogeneous sensitivities, it becomes difficult to attribute observed transition patterns to underlying hydrological processes rather than methodological artifacts. Specifically, imbalances in the relative frequency of detected floods versus droughts can artificially bias the apparent prevalence and rapidity of one transition direction over another, while spatial heterogeneity in detection sensitivity confounds regional comparisons and masks true hydroclimatic controls. While alternative event identification approaches with spatially or temporally uneven detection characteristics may be appropriate for specific applications—such as flood risk

assessment where hazard exposure is inherently non-uniform—such methods are not pursued in this analysis. Instead, we prioritize methodological consistency to isolate genuine hydrological dynamics from definition-dependent artifacts, thereby enabling robust inference about the physical drivers of extreme transition events.



**Figure S4:** Map with McCabe and Wolock (2022) regional clusters. Streamgages that were not included in the original McCabe and Wolock (2022) streamgages were assigned to the region of the nearest streamgage. Note that we changed the name of region 5 from Central Plains and Forests to Central Forests to avoid confusion with region 7 (Central Plains). We also modified region 6 to be North Central rather than Northern Central to align with region 10.



that panel e is the total number of events, not just the sub-seasonal events. Names corresponding to hydrologic region numbers are provided in Fig. A4. 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 Figure S4 for a map of regional clusters, with names and numbers.



Figure S6: Regional seasonality plots: The fraction of DtF transitions that occur under 30 days for each month, split into the 12 different flow regions from McCabe and Wolock (2022). Refer to Figure S4 for a map of regional clusters, with names and numbers.

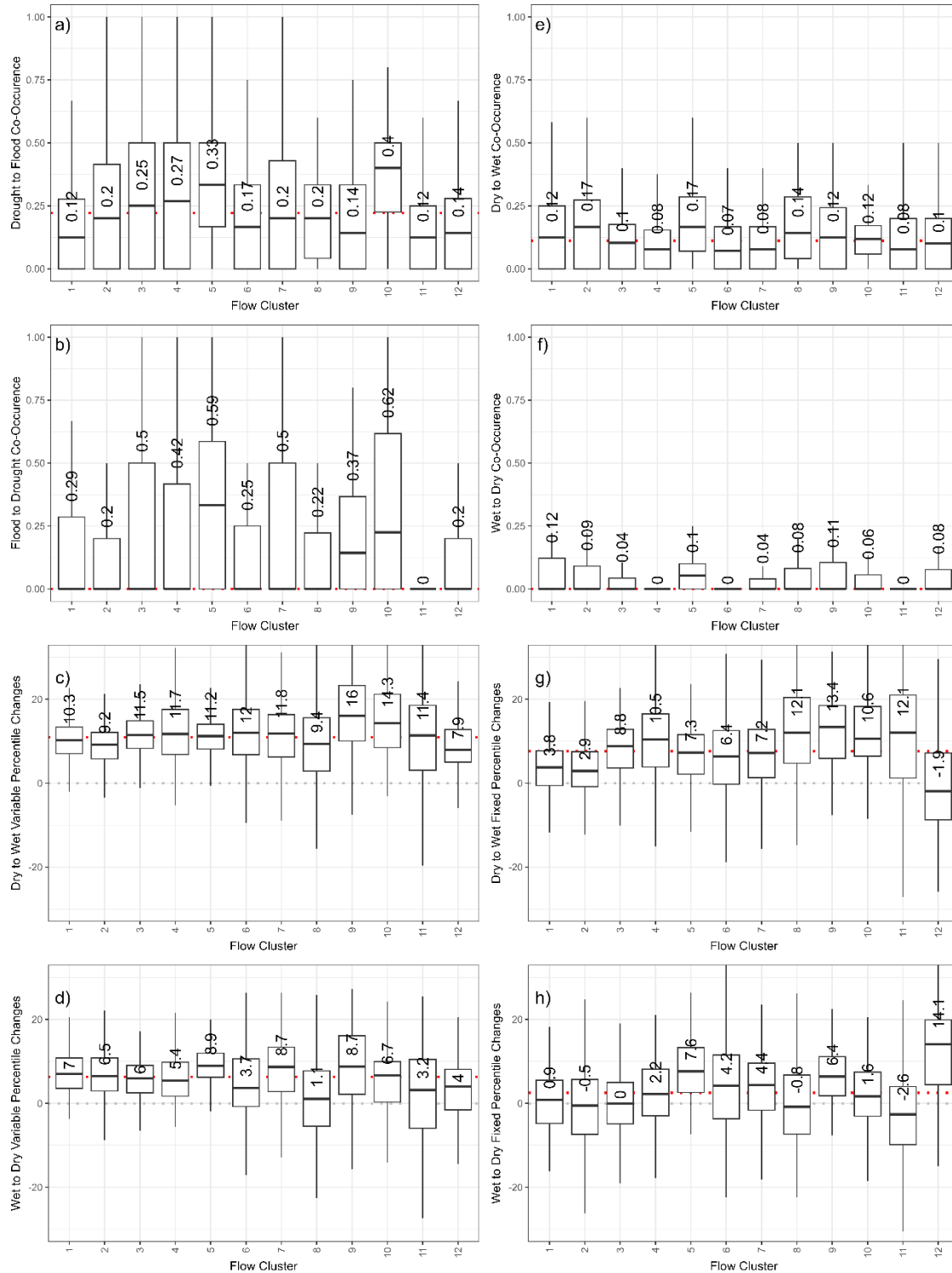


**Figure S7:** Regional seasonality plots: The fraction of FtD transitions that occur under 90 days for each month, split into the 12 different flow regions from McCabe and Wolock (2022). Note that in some regions, there are relatively few transitions beginning in certain months. For example, only 15 flood-to-drought (FtD) transitions start September in the Northwest region over the full period, and as a result the 4/15 of these transitions which occur in under 90 days results in a high fraction. Refer to Figure S4 for a map of regional clusters, with names and numbers.



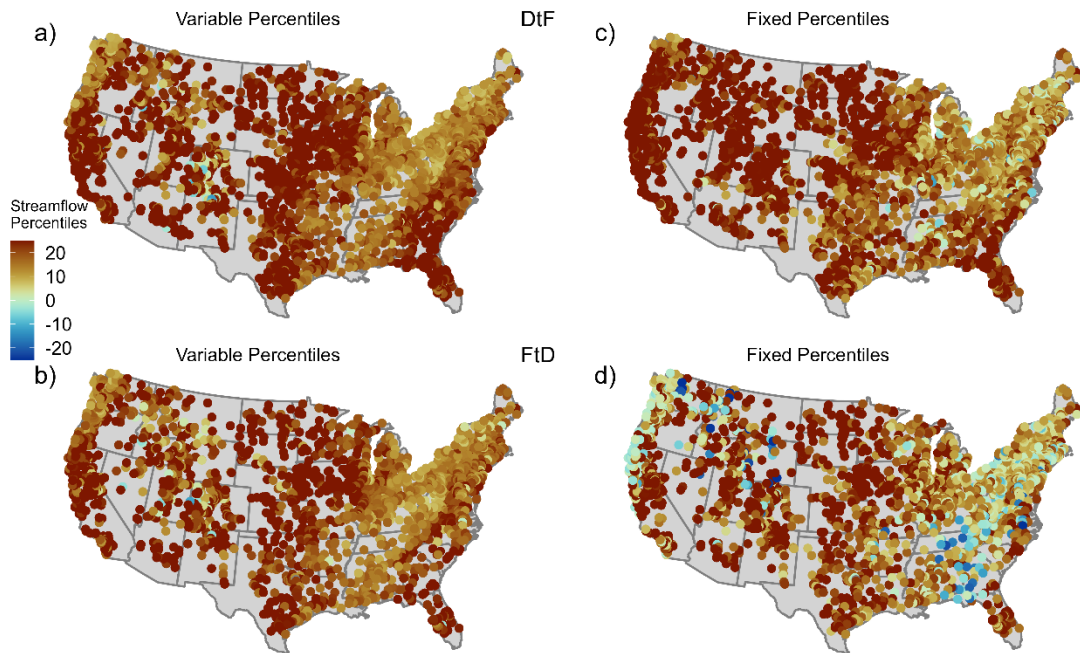
**Figure S8:** Box plots with additional information that did not fit in the box plots in the main text. Plots for fraction of impactful transitions (a transition that occurs within 90 days and involves at least a 50-percentile shift in fixed streamflow percentile space) (a) and median transition time (b) for synchronicity and concentration basin types, the fraction of impactful transitions for different land-cover and basin size (small  $\leq 100\text{km}^2$ , medium  $> 100\text{km}^2$  and  $\leq 1000\text{km}^2$ , large  $> 1000\text{km}^2$ ) classes (c), and the fraction of impactful transitions (d) and median transition time across regions and land cover types. Names corresponding to hydrologic region numbers shown in parts d and e are provided in Fig. A4. 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 Figure S4 for a map of regional clusters, with names and numbers.

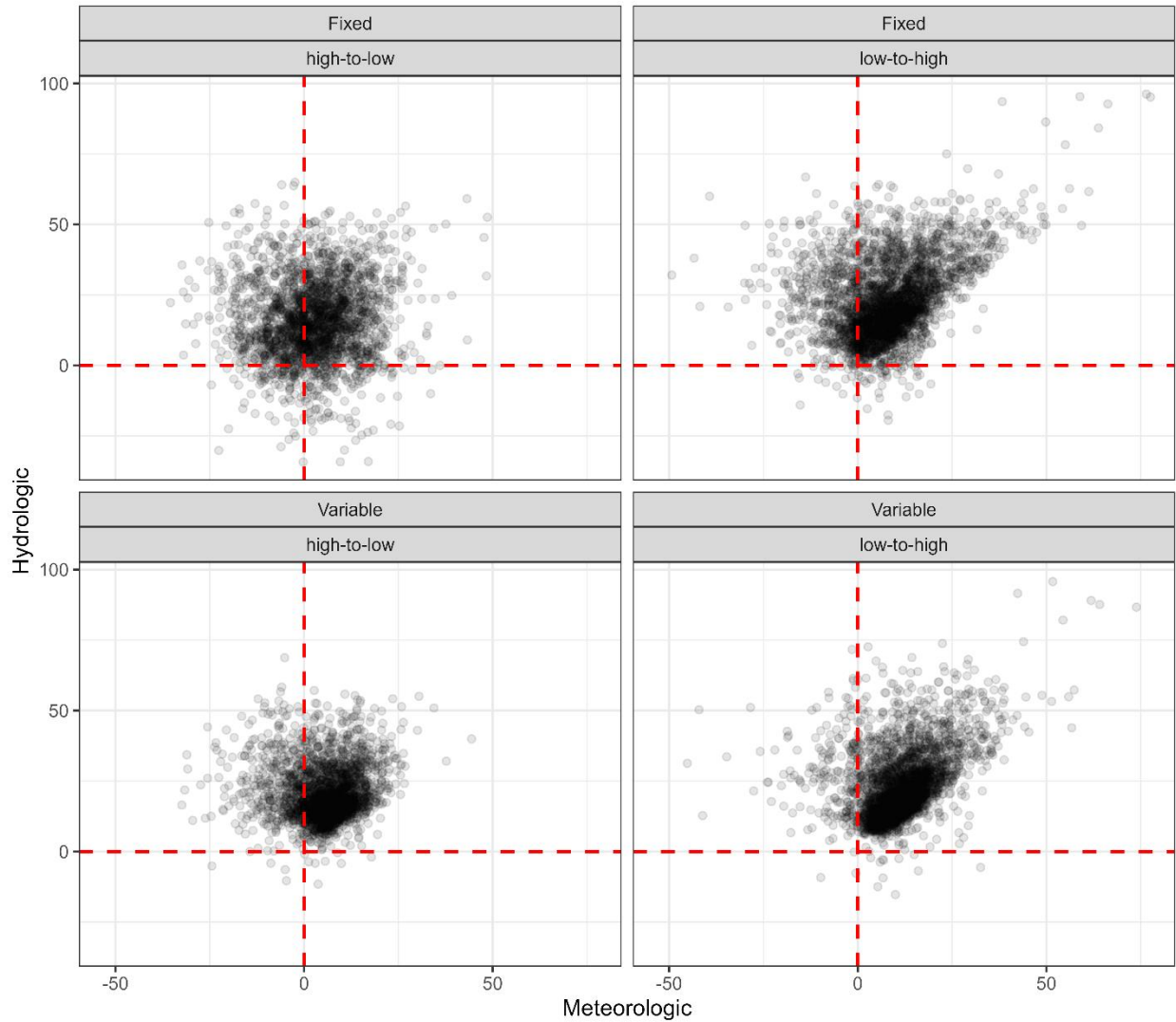


**Figure S9:** Box plots of variables corresponding to **Error! Reference source not found.** split up by hydrologic regions. Names corresponding to hydrologic region numbers are provided in Fig. A4. Median values are printed in text, although for the flood-to-drought (FtD) (b) and wet-to-dry (f) boxplots, the 75<sup>th</sup> percentile was printed because the median

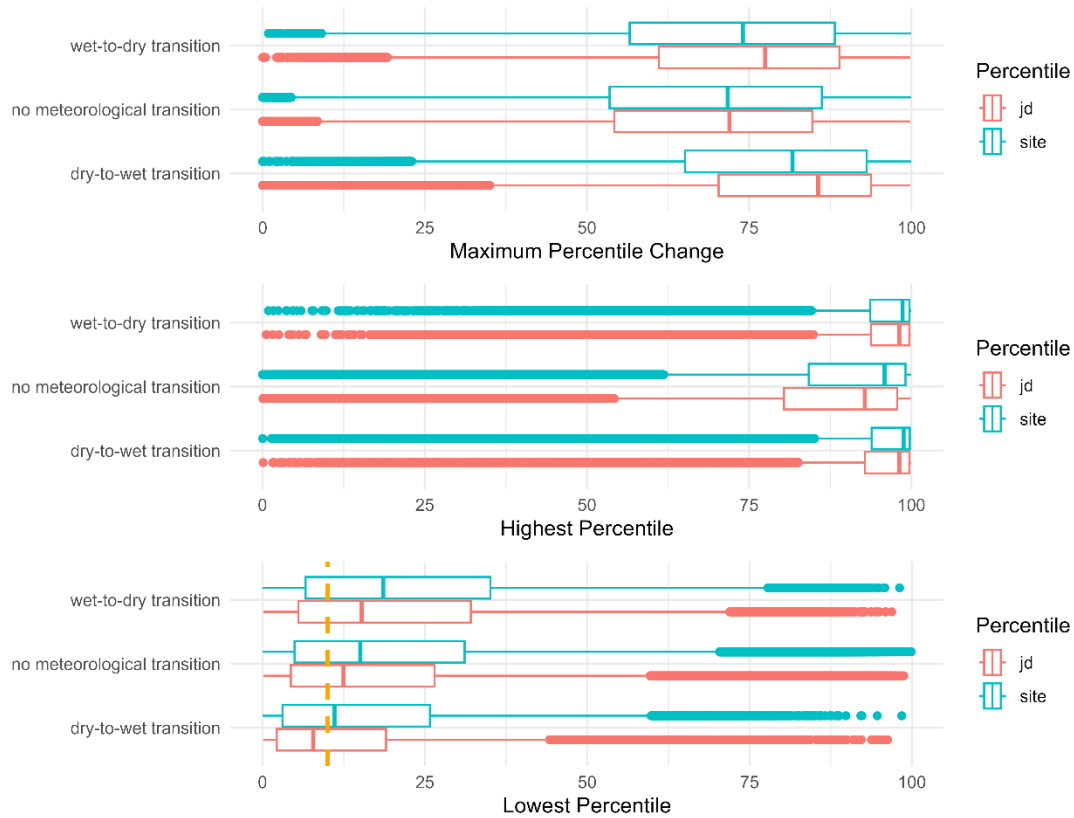
value was zero in most cases. For each box plot, the center line indicates the median and the box boundaries represent the interquartile range (IQR). Whiskers extend to the furthest data point within 1.5 times the IQR from the box boundaries; individual outliers falling outside this range are omitted from the display for visual clarity. Horizontal dotted lines indicate the global median values in red, and zero in grey. Refer to Figure S4 for a map of regional clusters, with names and numbers.



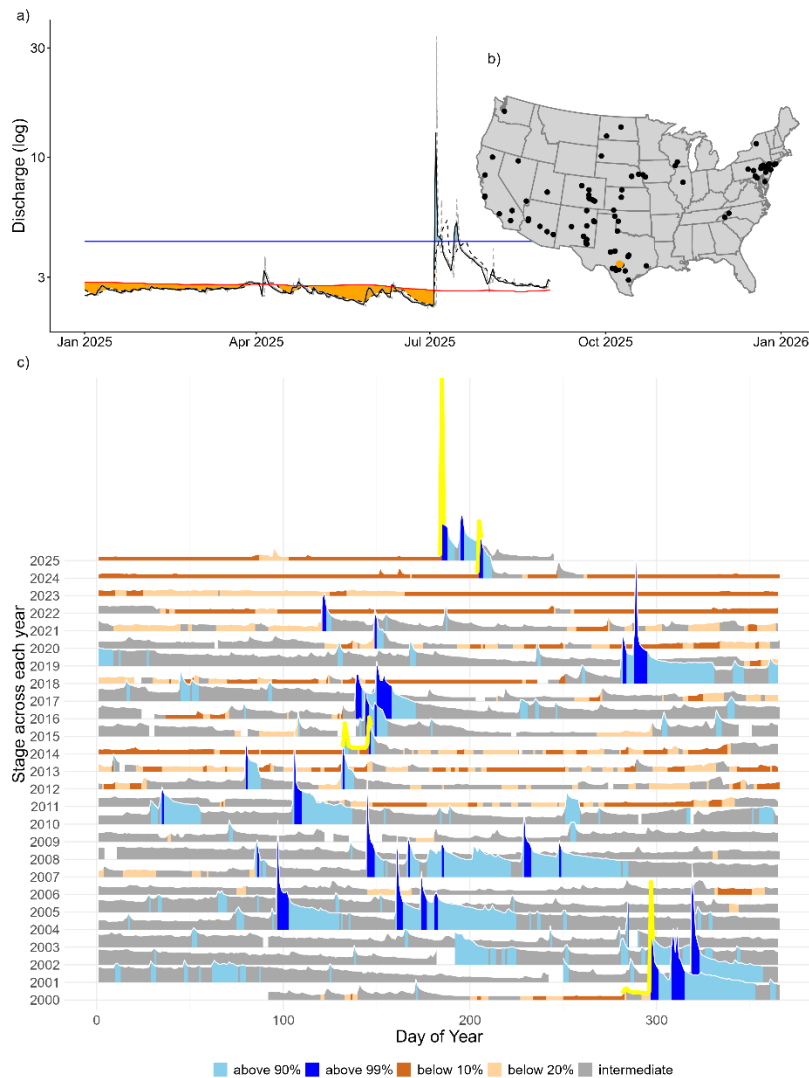
**Figure S10:** The maximum changes in variable and fixed streamflow percentile during drought-to-flood (DtF) and flood-to-drought (FtD) transitions relative and 90 preceding days relative to the median percentile changes during all periods.



**Figure S11:** Scatter plots comparing the maximum changes in the variable and fixed streamflow percentiles during the season of meteorological and hydrological transitions and 90 preceding days relative to the median percentile changes during all periods. The x-axes are the changes streamflow percentiles during meteorological transitions relative to the normal change across all periods. The x-axes are the changes streamflow percentiles during hydrological transitions relative to the normal change across all periods. The top row is fixed streamflow percentiles while the bottom row is variable percentiles. The left column is high-to-low transitions, i.e., wet-to-dry and flood-to-drought. The right column is low-to-high transitions, i.e., dry-to-wet and drought-to-flood. Each point represents the average changes relative to normal for a given site.



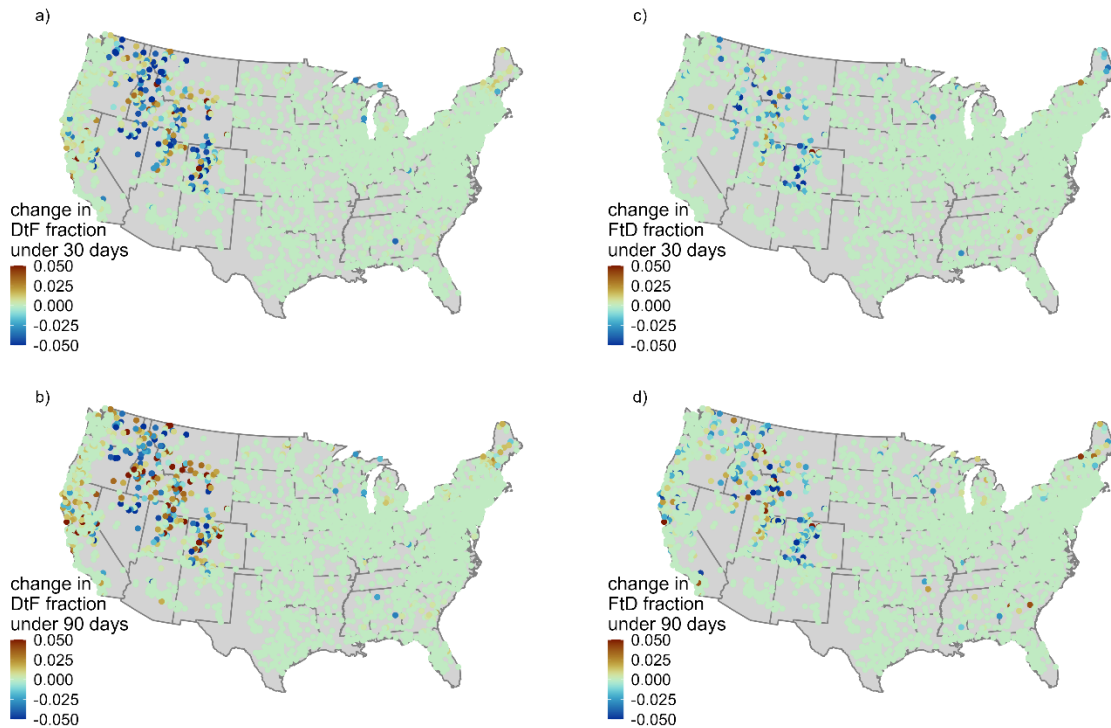
**Figure S12:** Box plots for seasons with wet-to-dry, dry-to-wet, or no meteorological transitions. Variable streamflow percentiles are in red labeled “jd”. Fixed streamflow percentiles are in blue labeled “site”. For each box plot, the center line indicates the median, the box boundaries represent 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. The vertical orange dotted line represents the drought threshold.



**Figure S13:** Panel a) shows a timeseries of a drought-to-flood (DtF) transition on the Guadalupe River above Bear Creek at Kerrville, TX (U.S. Geological Survey station 08166140; U.S. Geological Survey, 2026) in 2025. Here, the black line is daily streamflow, while the dotted line is instantaneous streamflow. Panel c) shows a timeseries of stage during 2000–2025 with DtF transitions identified in yellow. Panel b) shows the location of the Guadalupe River streamgages (orange) and all other streamgages (black) that experienced a DtF transition between 1981–2024, where flows shifted from below the 1st percentile to above the 99th percentile within a single day.

Streamflow data for the Guadalupe River were downloaded from the U.S. Geological Survey National Water Information System (NWIS; U.S. Geological Survey, 2026) using the dataRetrieval package (Hirsch and De Cicco, 2015; R Core Team, 2024). Because data are only available from 2000 to the present (2025), the historical reference period was set to 2000–2020. Stage rather than discharge was used to better capture this extreme event because approved discharge values were not available at the time of analysis (U.S. Geological Survey, 2026). Aside from this adjustment, the methodology

was identical to that applied across the other sites. To contextualize the transition at this site, results were plotted to highlight the rapidity and magnitude of the transition. Comparison against the full set of DtF transitions available during 1981–2025 shows that this Guadalupe River transition is among the rare cases in which flows shifted from below the 1st percentile to above the 99th percentile within a single day, placing it alongside only a small number of comparable transitions observed across the network.



**Figure S14:** The change in the fraction of transitions that occur under 30 (a, b) and 90 (c, d) days when a fixed percentile shift is required. Blue colors mean that when a fixed percentile shift is required that the fraction of transition under 30 or 90 days decreases, while brown colors mean that the fraction of transitions under 30 or 90 days has increased.

## Supplemental Information References

Hirsch, R., and De Cicco, L.: User Guide to Exploration and Graphics for RivEr Trends (EGRET) and dataRetrieval: R Packages for Hydrologic Data, U.S. Geological Survey, <https://doi.org/10.3133/tm4A10>, 2015.

Lisonbee, J., Woloszyn, M., and Skumanich, M.: Making sense of flash drought: definitions, indicators, and where we go from here, *Journal of Applied Service Climatology*, 1–19, <https://doi.org/10.46275/JOASC.2021.02.001>, 2021.

McCabe, G. J., and Wolock, D. M.: Clusters of monthly streamflow values with similar temporal patterns at 555 HCDN (Hydro-Climatic Data Network) sites for the period 1981 to 2019, U.S. Geological Survey data release, <https://doi.org/10.5066/P9ETG2RP>, 2022.

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