What is a drought-to-flood transition? Pitfalls and recommendations for defining consecutive hydrological extreme events

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Abstract. Research into rapid transitions between hydrological drought and flood is growing in popularity, in part due to media-reported catastrophic impacts from recent events. Droughts and floods are typically studied as events that are independent from one another, and thus, a clear definition and assessment of the methods used to define consecutive drought-to-flood transition events does not yet exist. Here, we use a series of eight catchments that have experienced real-world impacts from drought-to-flood transitions as case studies. We assess the suitability of, and differences between, event selection methods applied to observational data. We demonstrate that different threshold level methods can alter the characteristics of selected events. The number and timing of transitions differs substantially between threshold level approaches in highly seasonal regimes as opposed to those with a weaker seasonality. The time period used to define the maximum interval between drought and flood also influences whether transitions are detected. We show that the probability of a transition occurring within a set time window could vary substantially between different methodologies and catchments. We also show that previously applied methodologies would likely fail to detect transition events that have been broadly impactful in the historical record. For the eight case study events taken from media, governmental and scientific reports, only three of the transitions were successfully detected. We qualitatively assessed the streamflow time series of the case study catchments, and outline a number of potential pitfalls in the event detection process. Finally, we make recommendations regarding methodological choices in the context of potential impacts of interest, and outline some priorities for future methodological development and research into transitions.

1 Introduction

Consecutive drought and flood events have received considerable media attention in recent years due to severe impacts resulting from large events. For example, in Italy, a severe multi-year drought in the Po River region, described as one of the worst on record (Montanari et al., 2023), was followed by the May 2023 flood in Emilia Romagna, which affected the lower tributaries of the Po. The flood event resulted in levee breaches, landslides, widespread infrastructure damage, and loss of life (Martina et al., 2024). Similarly, from January 2010 to March 2012, large parts of England and Wales experienced a severe drought, which was ended abruptly by the wettest April to June period on record for much of the region. This lead to heavy rainfall and flooding through the summer and autumn (Kendon et al., 2013; Parry et al., 2013; Terry Marsh et al., 2013). Within the research community, there is growing recognition that although droughts and floods represent opposite hydrological hazards, there is added value in studying them in relation to one another. These extreme events can exacerbate the impacts, extent, or magnitude of each other under certain circumstances (Brunner et al., 2021; Ward et al., 2020).

Drought-to-flooded transitions, that is, floods that occur shortly after hydrological drought, challenge the effectiveness of disaster risk reduction measures that target only one hydrological extreme at a time, highlighting the need for integrated strategies that address both floods and droughts together (Ward et al., 2020). Management strategies may not be easily shifted to handle one extreme after the other, and measures taken to mitigate one extreme may adversely effect the other. For example, quickly shifting between water storage strategies in dual-purpose reservoirs, which aid in the management of both flood and drought risk, can be difficult (Ward et al., 2020; Lal et al., 2020; Rogers and Tsirkunov, 2010). Further, wet and dry cycles can challenge the integrity of infrastructure. For example, drought can increase the chance of failure of levees and dikes during flood events, which, in turn, can lower defenses against flood risk, and reduce water supply during subsequent drought periods (Ward et al., 2020; Van Baars and Van Kempen, 2009; van Huijgevoort et al., 2012; Hubble and De Carli, 2016). Socioeconomic challenges can stem from insufficient recovery time between events and shifting land use practices during prolonged drought periods (Barendrecht et al., 2024; Ward et al., 2020; Gallina et al., 2016). Water quality issues may arise from pollutant accumulation during drought that is mobilized together with topsoil loss during subsequent runoff events (Barendrecht et al., 2024; Mishra et al., 2021; Levy et al., 2016; Laudon et al., 2005; Wurtsbaugh et al., 2019; Effler et al., 2001).

Further concerns center around physical processes. For example, changes in soil properties during drought may result in increased runoff in some locations (Descroix et al., 2013; Matanó et al., 2024). Beyond this, regime changes due to climate and environmental change may increase the frequency of rapid drought-to-flood transitions, as evidenced by increases in rain on dry soil events in some regions (Tarasova et al., 2023). Changes in soil infiltration rate and runoff are often cited as a cause for increases in surface runoff during precipitation events following dry periods (Gimbel et al., 2016; Barendrecht et al., 2024).

From a meteorological or atmospheric perspective, this topic has received a lot of recent attention. For example, Swain et al. (2025) reviewed the current literature on hydroclimate volatility (i.e., sudden, large and/or frequent transitions between opposite extremes). They further introduced a formal definition of the concept of "hydroclimatic whiplash" in which the Standardized Precipitation Evapotranspiration Index is used to define swings in atmospheric condition. Swain et al. (2025) show increasing hydroclimatic volatility, including rapid swings between wet and dry states in the atmosphere. Others have similarly shown an increasing probability of risk from an intensification of rapid swings between hydroclimatic extremes, relying on standardized indices (Casson et al., 2019; Na and Najafi, 2024). Although rapid changes between wet and dry conditions have been widely studied in the meteorological sciences, attention to this phenomenon is relatively new in hydrology.

To our knowledge, only a few large sample analyses of drought-to-flood transition events have been published to date. Götte and Brunner (2024) investigate the distribution and frequency of drought-to-flood transition occurrence in the United States and highlight that transition times vary widely within and between catchments. They find that a majority of detected transitions occur within the typical high flow season, and show that overall a majority of transitions are driven by snow melt, especially in high-altitude catchments, representing a transition from winter low to spring high flow. Matanó et al. (2024) explore the historical drought-to-flood transitions at a global scale and argue that, by their definition, in which droughts are defined under a variable threshold and floods over a fixed monthly threshold, 24% of floods globally have been preceded by drought conditions. Several papers have been published that use standardized index approaches to further explore abrupt switches between dry and wet periods in streamflow (Liu et al., 2016b; Cui et al., 2025; Li et al., 2016, e.g.).

Interest in interactions between drought and floods is also increasing in a more general sense. Recently, Barendrecht et al. (2024) performed a global review of the drivers and impacts of drought-to-flood transitions. The authors demonstrated the potential for increased impacts, the importance of short rainfall events as drivers of transitions, and highlighted the relative scarcity of research into consecutive drought and flood events. Alves et al. (2023) further highlighted that research into the interplay between floods and droughts is still limited from the perspective of risk and impacts and refer to an increase in published research on the subject in recent years. Ward et al. (2020) argued for the need to research droughts and floods together, outlining how risk deduction measures that target one of these extremes can have unintended impacts on the other hazard. Di Baldassarre et al. (2017) argued for the need to model the interplay of the two hydrological extremes due to the ways in which human responses to drought may worsen flood risk, and vice versa. Finally, Brunner et al. (2021) discuss challenges in modeling droughts and floods and argue that understanding their interactions is essential for the development of management strategies.

Although scientific interest in the topic of drought-to-flood transitions is growing, the definition of a drought-to-flood transition event is not yet widely agreed upon. Detection of drought and flood events individually is usually performed using annual maxima/minima or threshold level approaches applied to the original streamflow time series (Meylan et al., 2012). The application of threshold level methods for drought and flood detection requires a number of choices, including the choice of threshold level approach and the threshold level itself, smoothing and aggregation of streamflow time series, and event merging windows (Stahl et al., 2020; Van Loon, 2015). Depending on these choices, different drought and flood events may be identified, and the characteristics of those events can differ substantially (Tallaksen and Van Lanen, 2023). For example, drought duration and severity could vary widely, as could the physical characteristics of these events. A given methodological choice may therefore result in the selection of transition events that differ in their drivers and characteristics (e.g., timing, severity, duration) when a large number of disparate catchments are studied (England Jr. et al., 2019; Tallaksen and Van Lanen, 2023). For instance, drought events identified using a seasonal or daily varying threshold delineate 'drought' in periods experiencing a deviation from the normal flow at that time of the year, whether or not it corresponds to absolute low flows or dry conditions. As an example, drought events caused by a delay in the onset of the snowmelt season may be detected. Although this deficit could conceivably have impacts, for example, abnormally low water levels could reduce hydropower generation at the time of occurrence, the reduction may be compensated by an increase in production later in the season (Hisdal et al., 2024b, a; Stahl et al., 2020; Tallaksen and Van Lanen, 2023). Depending on the context, these anomalies may or may not represent impactful events. Failure to detect and accurately identify drought-to-flood transitions which are of interest in an analysis could lead to ineffective management strategies, misleading impact quantification, inaccurate risk assessments, or incomplete process understanding. Thus, further investigation into, and consideration of, how the choice of threshold influences the identification and characteristics of events is needed for burgeoning research into drought-to-flood transitions to deliver broadly meaningful results.

~~The annual maxima/minima method is often applied to identify extreme events, however, in years without major extremes, the method may select relatively less extreme events, while in years with multiple extreme events, it may disregard other substantial events (Lang et al., 1999). Threshold-based approaches, instead, help to overcome these problems because they enable sampling of more than one extreme event per year by identifying all events above or below a certain threshold. Several different threshold level approaches exist. In particular, fixed annual or seasonal thresholds and temporally varying thresholds are popular. Fixed thresholds are often applied to identify flood events (commonly referred to as Peak Over Threshold approach), whereas fixed, seasonally, or daily varying thresholds are sometimes applied to identify drought events as periods with seasonal streamflow deficits. Such threshold-based approaches are sometimes also applied to standardized anomaly time series such as the standardized streamflow index (Vicente-Serrano et al., 2012; Vicente-Serrano et al., 2020), which are calculated by computing anomalies based on aggregated time series mirroring indices used in atmospheric sciences (Guttman, 1998). Although applying fixed annual or seasonal flood and drought thresholds on original time series leads to the identification of transitions from one extreme event to another, standardized approaches identify shifts as deviations from long term average flow conditions.~~

Here, we qualitatively and quantitatively assess a series of eight case study catchments and historical flood and drought events. We explore how the imprecision in definition of drought to flood transitions might lead to very different research outcomes, and we aim to better understand how to define drought-to-flood transitions. We are primarily focused on generating insight for contexts which require generalized definitions and approaches across a number of catchments. We focus specifically on drought and flood events identified in the original streamflow time series by applying threshold level approaches, rather than relying on standardized indices. This choice was made to ensure that the case studies pertain to impactful *events*. Further, streamflow, to some extent, already represents an aggregate value, and because standardized indices can be very sensitive to the temporal aggregation period (Lema et al., 2024). "The choice to look at events only, rather than periods of anomalous flow, as with standardized indices, was made because we are interested in hydrological extremes and standardized meteorological extremes may not translate to hydrological response (Brunner et al., 2025). Further, because the use of standardized indices such as the standardized streamflow index (SSI) introduces uncertainty to the method because used in its calculation, including choice of distribution and fitting method (parametric method) as well as choice of non-parametric methods (Tijdeman et al., 2020)." We compare three different threshold level approaches applied to the case study catchments, and compare the detected transition events with media reported events in both a quantitative and qualitative manner. In the quantitative analysis, we primarily focus on the characteristics of the detected transition events, asking:

- How effectively do the methods detect the documented drought-flood transition events in each case study?
- How does seasonality impact the detection of events?
- How and why do the number and type of transition events detected differ among methods?

In the qualitative assessment, we discuss potential pitfalls in the definition of transition events based on existing literature and present these along with examples from the case study catchments.

The reported case study events allow us to evaluate the performance of transition detection methods against flood and drought events that have been reported by media outlets and national authorities. We use the documented media events to evaluate the methods, assuming that impactful, media-reported events can be seen as benchmark events for all methods. This approach allows us to contextualize the definitions of drought-flood transitions relative to observed events in the case study analysis, and assess to what degree transitions are a concern in the selected catchments.

2 Methods and data

2.1 Case studies

We select eight case study catchments (Figure 1) for which media and/or scientific reports describe a flooding event following drought conditions, and for which daily or higher resolution streamflow data are available. The case study catchments include the Daintree River in Australia, the Ventura River in California, USA, the Rio Colorado in central Chile, the River Aire in Northern England, the River Savio in Italy (a tributary of the Po), the Emme in Switzerland, the Ulvåa River in Norway (a Tributary of the Glomma), and the Llano River in Texas, USA. Catchment information, including gauge ID and data sources, catchment area, and the drivers of the case study events are included in the supplementary materials (Table S1).

Media reported drought-to-flood transitions for each catchment are referred to as "case study events". Drought impacts for these case study events range from relatively minor e.g. altered sensitivity to salinity in mangrove plants in Australia (Beckett et al., 2023), e.g. to wide spread policy reform due to an energy crisis caused by a reduction in water available for hydro power in Chile (Murillo and Foulon, 2006). Similarly wide ranging impacts were reported for floods. Some floods resulted in minor road closures and water inside buildings, e.g. in the Swiss case study (Martin Bürki, 2022; Käthi Liechti, 2023; Bundesamt für Umwelt (BAFU), 2023) whereas others, such as the Italian case study, resulted in multiple deaths, landslides, and billions of Euros in reported losses (Povoledo, 2023; Eric Stober, 2023; Frances D'Emilio, 2023; noa, 2024, 2023b). A non-comprehensive table listing reported impacts and event occurrence dates is presented below in Table 1. In addition to the case study events, we also analyze the complete time series of each of the corresponding catchments.

We define "reported" drought periods based on the earliest reported start date and latest reported end date found in the media, scientific, or governmental reports of the events as in Table 1. For "reported" flood events, we are primarily concerned with the first day of flooding to define a transition. For this reason, we use only the earliest reported start date, as opposed to the date of the most severe flooding. It is possible that media reports may be misleading in terms of event location of timing. We aimed to validate event occurrence and the correspondence of spatial area by allowing for buffer periods around flood events, confirming the presence of a flood on the expected dates in the time series of all cases, relying on more than one report for all events, and seeking scientific and governmental reports which listed specific catchment IDs rather than news media. Previous research has also indicated that media reports can be reliable and valuable sources of information as to when and where impacts occur

(Stahl et al., 2016). References and descriptions of the events are listed in Table 1. It is worth noting that validation in the case of drought was more difficult, given the generally wider spatial areas, and varied definitions used in reporting.

Table 1: Description of case study events

Case Study	Reported Event Dates	Reported Drought Impacts	Reported Flood Impacts	Regime description
Australia: Daintree River	Drought: Aug. 2018-Dec. 2018; Flood: Dec. 25, 2018	Record high temperatures, below average precipitation and streamflow, increased estuarine salinity affecting tree growth (1, 2)	Initial flooding: major flooding, halted ferry operation, inundation and damage to roadways. Flooding continued and intensified into January of the following year, eventually beating a 118-year record and declared a nationally significant emergency with severe impacts (3-8)	Dominated by a monsoonal system with a pronounced winter dry season.
California, USA: Ventura River	Drought: 2020-2022; Flood: Jan. 10, 2023	Large-scale meteorological and hydrological drought resulting in wildfire damages, historic low reservoir storage, and major economic losses in the agriculture, processing, and tourism industries (9-12)	Estimated 5 to 7 billion US dollars in economic losses, streambank erosion, damaged sewer lines, loss of life, people rescued from river, evacuations, school closures, and sinkhole formation (13-17)	Moderately strong seasonal pattern, typically experiences large storms during the winter season; pronounced low flow season, during which streamflow is frequently zero.
Chile: Rio Colorado	Drought: 1998-1999; Flood: Jun. 23, 2000	National-scale energy crisis due to low reservoir levels resulting in major policy reform (18-24)	Yellow danger warning issued by the National emergency management agency, 4000 people evacuated, and a tripling of water released from the Colbún Machicura hydroelectric power plant to minimize flooding (25, 26)	Strong seasonal snowmelt peak, but also experiences large rainfall driven floods in early winter prior to the start of the snowmelt season.
England: River Aire	Drought: Jan. 2010-Mar. 2012; Flood: April 15, 2012	Most severe in Southern England but extended into Yorkshire, where the Aire is located. Low reservoir levels and hosepipe bans across north-west England affecting six million consumers in Spring 2010. Fires, low water levels, and agricultural losses throughout the following year (27-30)	Flooding started with minor events in April 2012, followed by a severe flood in September 2012. Early floods resulted in minor impacts, high water levels, and flooded roadways. September flood resulted in reported warnings issued, flooded roadways, road closures, and pumping (31-34)	Rapid runoff in the upper parts of the catchment; wide meandering course through the lower section. Flooding predominantly driven by heavy precipitation events in the winter season. Relatively variable regime. (35)
Italy: River Savio (Tributary of the Po)	Drought: Jan. 2022-May 2023; Flood: May 2, 2023	Reported "worst" hydrological drought in 2 centuries in 2022, record low water levels, increased riverine salinity, damage to crops, combined losses over 6 billion Euros (36-38)	First flood on May 2nd, followed by a larger event on May 16th. 17 people dead in Emilia Romagna, approximately 400 landslides, thousands evacuated, damage to agricultural lands, hundreds of roads closed or destroyed, more than 10 billion euros in estimated losses, 7 months of typical rainfall in 2 weeks (39-46)	Dry in summer; wet spring with precipitation mainly as rainfall, some snowfall in upper portion of the catchment. Some seasonal pattern but relatively variable (44).

Case Study	Reported Event Dates	Reported Drought Impacts	Reported Flood Impacts	Regime description
Norway: Ulvåa River (Tributary of the Glomma)	Drought: Jun.-Aug. 2018; Flood: Oct. 14, 2018	Large-scale drought. Grass and bush fires, agricultural subsidies on imported goods, water restrictions, increased electricity costs (48-51)	Flash flood event due to a combination of high temperatures (early snowmelt) and rainfall, damages to agricultural land, losses of stored animal feed (stock already low due to drought), flooded streets and homes in the nearby region (52). Impacts on Ulvåa River somewhat limited due to small population size but is proximate to areas with reported impacts	Strong snowmelt cycle and dominant winter low flow season.
Switzerland: River Emme	Drought: May 2022-Sep. 2022; Flood: Jul. 04, 2022	Severe drought and heat waves across much of Europe, record high water temperatures and 0 flow in some places on the Emme caused damage to aquatic life eventually resulting in fishing ban, and estimated 10 million CHF in agricultural losses in Switzerland, in addition to increased heat related deaths (53-58)	"Flood wave" passed highest "Danger level", some bridges and roads unpassable, water up to 50 cm inside some buildings, flow volume increased over 200x within one day, eroding banks and resulting in a debris flow (59-62)	Small, flashy, subalpine catchment with some snowmelt influence. Floods are predominantly driven by rain events.
Texas, USA: Llano River	Drought: Jan 2023-Oct. 2023; Flood: Oct. 26, 2023	"Exceptional" drought throughout catchment according to the United States Drought Monitor, record low water levels on large downstream reservoirs, public water use restrictions, wide spread wildfires, 0 flows recorded (63-67)	Some inundation of structures and roads, dramatic sudden increase in downstream reservoir levels, reservoirs failed to recover to normal conditions, but drought condition improved in the region (66-67)	Semi-arid with some groundwater inflow. Drier in summer. Responds rapidly to precipitation and is subject to frequent large convective storms (68-70)

References: 1. Jess Fagan (2023), 2. Beckett et al. (2021), 3. Staff Writers (2018), 4. Rebecca Hyam and Nick Wiggins (2019), 5. Steve Turton (2023), 6. Steve Turton (2019), 7. noa (2020), 8. Press (2019), 9. Medellín-Azuara et al. (2022), 10. Escriva-Bou et al. (2022), 11. Jay Lund and Andrew L. Rypel (2023), 12. Amanda Sheffield and Julie Kalansky (2022), 13. Andrew Freedman (2023), 14. Navarro (2023), 15. Jonathan Lloyd and Belen De Leon (2023), 16. Richard Davies (2023), 17. KCAL News Staff (2023), 18. Murillo and Foulon (2006), 19. Serra (2022), 20. Nacional (1999), 21. Kim et al. (2022), 22. Garreaud et al. (2017), 23. Oertel et al. (2020), 24. noa (2000b), 25. noa (2000c), 26. noa (2000a), 27. Parry et al. (2013), 28. Kendon et al. (2013), 29. Terry Marsh et al. (2013), 30. noa (2012a), 31. Wainwright (2012), 32. Helen Mead (2024), 33. noa (2012b), 34. Harvey (2012), 35. noa (2009), 36. Montanari et al. (2023), 37. Paolo Santalucia (2023), 38. Chelli (2023), 39. Povoledo (2023), 40. noa (2023c), 41. noa (2023b), 42. Frances D'Emilio (2023), 43. Eric Stober (2023), 44. Arrighi and Domeneghetti (2024), 45. Valente et al. (2023), 46. Ascione and Valdano (2024), 47. Cilli (2020), 48. Bakke et al. (2020), 49. Nina (2018a), 50. Nina (2018b), 51. Reidun Gangstø Skaland et al. (2019), 52. Nina Berglund (2018), 53. noa (2022c), 54. noa (2022a), 55. Ballester et al. (2023), 56. noa (2022b), 57. Le News (2022), 58. Jorio (2023), 59. admin (2022), 60. Gaudenz Flury and Daniela Schmuki (2022), 61. Martin Bürki (2022), 62. Käthi Liechti (2023), 63. noa (2023a), 64. Morrissiey (2023), 65. Kevin Vu (2023), 66. Anna Skinner (2023a), 67. Anna Skinner (2023b), 68. Furl et al. (2018), 69. Nielsen-Gammon et al. (2005), 70. Smith et al. (2000).

In addition to *reported* drought-to-flood transition events, the case study catchments were selected to represent a range of hydrological regimes to facilitate a higher degree of generalization across hydro-climates. We do not use a formal definition for hydrological regimes because these can vary widely (Brunner et al., 2020). Instead, we qualitatively describe the regimes based on the degree they are influenced by snow, seasonality in the median, high, and low streamflows, and variability in the daily flow regime (Table 1). In this study, we considered several highly seasonal catchments with clearly defined high and low flow seasons and low streamflow variability in the low flow season, such as monsoonal types (River Daintree in Australia) and snow dominated regimes (Ulvåa River in Norway), mixed regime types experiencing influence from both snowmelt and rainfall (Rio Colorado in Chile, Savio River in Italy) and predominantly pluvial regimes (Ventura River in California, USA, River Aire in England), including one semi-arid regime (Llano River in Texas, USA) and one highly flashy sub-alpine regime (Emme River in Switzerland; Figure 1). These regimes represent different degrees of seasonality, ranging from low to strong seasonal patterns, and the primary drivers of floods within the catchments are known. In addition to the information presented here in Table 1, further descriptions of the case study events are included in the discussion as relevant.

2.2 Data

In addition to the case study events, we used daily mean streamflow data for the complete time series in the selected catchments. The length of the time series and the degree of missing values vary, but six of the eight catchments have daily streamflow series longer than 40 years with at least 95% coverage. The Chilean and Italian sites are an exception. In these catchments, 20 and 17 years of 95% complete data were available, respectively. Limited time series length can affect threshold level estimation in that flow during the available period may differ from long term conditions. However, this effect would be consistent across all threshold level approaches and methodological combinations in one catchment. These catchments were retained despite their relatively short length due to the importance of individual events and the intention to cover a wide geographic range. Although more complete data records are available for some catchments in both Italy and Chile, catchments that also reported major drought-to-flood transition events, could not be found at this time. In addition to daily mean streamflow data, sub-daily data was obtained for the catchment in Switzerland and used in the qualitative analysis. The hydrological data are taken from publicly available large sample and national hydrological datasets as described in Table S1.

2.3 Quantitative methods

2.3.1 Event detection approaches

We test and compare three different threshold level methods for drought, including (1) a daily varying threshold defined as a rolling percentile for each day of the year (across all years) plus 15 days before and after it. This 31-day window was selected because it offers sufficient smoothing to capture seasonal behaviour without over-smoothing, representing the monthly time scale (Van Loon and Van Lanen, 2012; Tallaksen and Van Lanen, 2023), (2) a seasonally varying threshold defined as two separate fixed thresholds, one for autumn and winter and one for spring and summer, and (3) a fixed threshold defined as a singular percentile of the complete time series (Figure 2 c., d., e.). Each of these three approaches is calculated from the

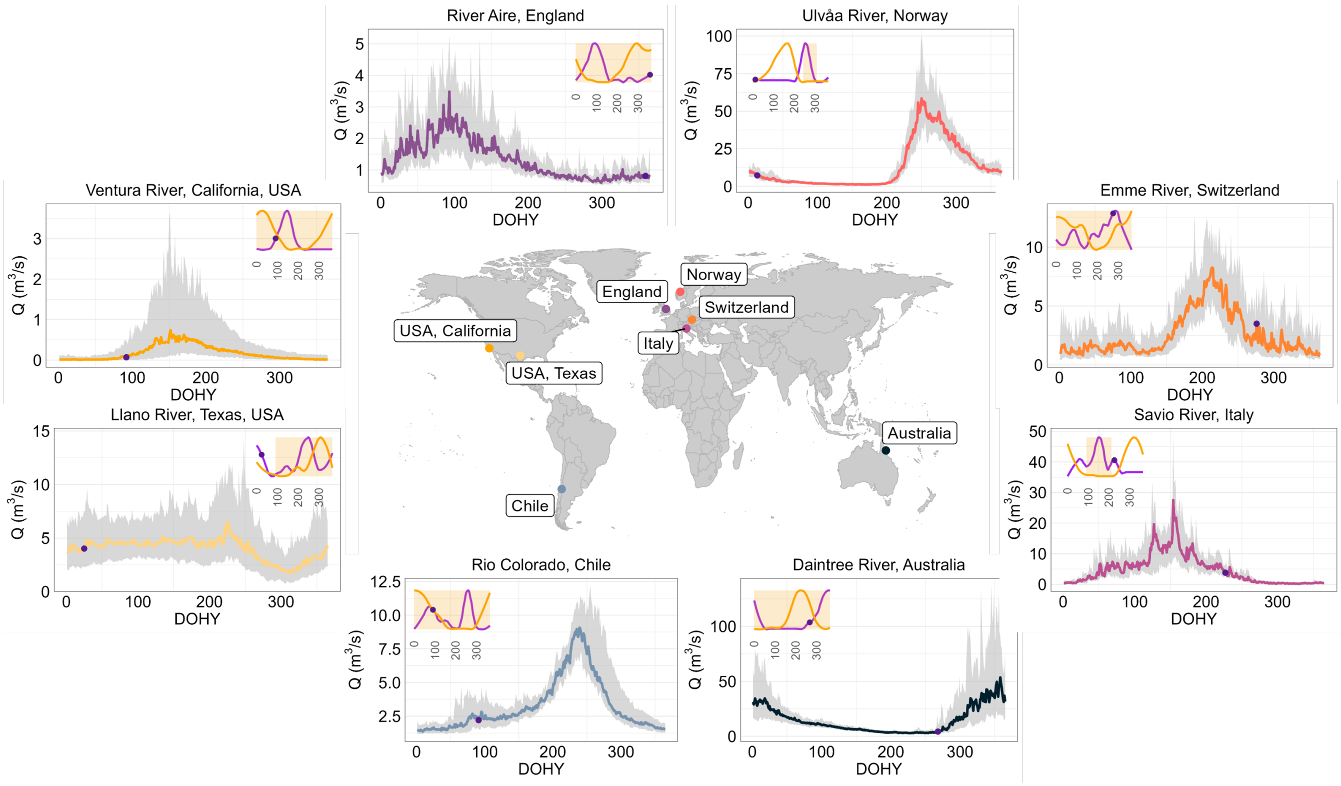

Figure 1. Regime plots showing the median hydrograph (bold line) for each case study catchment. The grey ribbon represents the inter-quartile range for each day of the hydrological year (DOHY), beginning on April 1st in the Southern Hemisphere and October 1st in the Northern Hemisphere. In the upper corner of each regime plot, the loess-smoothed Q99 frequency distribution is included as a purple line and the loess smoothed frequency distribution of streamflow days under the 20th percentile as an orange line. The timing of the reported case study drought event is presented as an orange overlay and the timing of the reported case study flood as a purple dot. Multi-year drought spans the entire year in these plots. Note that these sub-plots are frequency distributions, ranging between 0 and 1, where higher values indicate a relatively greater frequency of occurrence. These indicate how well extreme flood timing and typical low flow season timing correspond to the median regime.

smoothed daily streamflow time series, in which the previous 30 days are used to calculate a rolling mean for each day in the time series. The previous 30-days are used, rather than a centered period, so that rapidly occurring flood events do not result in an earlier drought end date. The thresholds are then are compared to the smoothed timeseries. All three approaches are commonly used in hydrological research, although each highlights different streamflow characteristics (Tallaksen and Van Lanen, 2023). Further, they have been previously applied for the detection of drought-to-flood transitions (Götte and Brunner, 2024; Matanó et al., 2024). Although there is some debate on whether it is appropriate to detect drought using a variable threshold, we refer to anomalously low flow periods detected by this method as "drought" here for simplicity of comparison between methods. It is important to note that droughts of different durations, intensities, drivers, and intermittency can occur and that each of these events can have different effects. The intention of this manuscript is to highlight pitfalls and discuss methodological differences in the context of impactful events. For this reason, we do not distinguish between drought and flood types in the current analysis.

The drought thresholds are calculated using a combination of the threshold level method (TLM) and the consecutive dry period method (CDPM) as described in van Huijgevoort et al. (2012) and demonstrated in (Figure 2.b.). This approach deals with zero-flow days in intermittent and ephemeral rivers by numbering consecutive zero flow days and calculating percentile statistics based on these counts. The intention of this approach is to allow for the detection of drought in zero-flow periods if the duration of the period is exceptional. We apply this approach equally for all threshold level types. We then identify negative streamflow anomalies using the thresholds and the 31-day smoothed (right-aligned) daily values (Figure 2.a.). Drought periods were required to have a duration of at least 30 days to avoid the inclusion of minor events (Van Loon, 2015; Brunner and Chartier-Rescan, 2024), and individual drought periods separated by less than 15 days were merged to singular events (Van Loon and Van Lanen, 2012; Tallaksen et al., 1997; Fleig et al., 2006).

We defined the flood threshold based on a percentile of the un-smoothed, original daily streamflow series and then selected events over the threshold using a POT approach where singular peaks were detected as floods. We do not require that peaks be independent because in the present context we are interested in the first date over the threshold, rather than the characteristics of the flood event. We test both a seasonal and a fixed threshold to detect events. A daily varying threshold is not considered for floods because it is not commonly used in the literature. The same approaches were applied to sub-daily streamflow for floods only, for the Swiss case study, as part of the qualitative analysis.

The percentile values used for the threshold levels were selected so that the average number of drought events detected across the case study catchments was 0.5+-0.005 per year and the average number of floods was 2+-0.005 per year regardless of the approach. This corresponds to drought thresholds ranging between the 12th and 15th percentiles depending on the methodology, and a flood threshold of 0.99 for both approaches. The number of drought events is lower than the number of floods, because drought events represent prolonged periods of low flow, whereas floods typically occur over short periods of hours to days. Defining the threshold based on the number of events (selecting the same number of events) was done so that the different threshold level approaches could be compared more fairly. We repeated the event detection approach using a range of threshold levels until the desired number of events was selected regardless of methodology. Alternatively, the same percentile value could have been used for all methods. Threshold level methods may result in the selection of a proportion of streamflow which is not equivalent to the stated percentile (Brunner and Voigt, 2024), in part because of the imposed minimum duration for drought periods (30 days). Although this may not have given the same number of events, it would have provided the same number of days below the threshold.

2.3.2 Definition of drought-to-flood transitions

Similar to previous work (Götte and Brunner, 2024; Matanó et al., 2024), we consider events to represent a transition by defining a maximum time interval between events. Here, if the time interval between the end of a drought (the date on which smoothed streamflow exceeds the drought threshold) and the start of a flood (the date on which streamflow exceeds the flood threshold) is less than 90 days, we consider this to be a drought-to-flood transition. We subdivide these time intervals into "rapid" (14 days) and seasonal transitions (90 days) as in Götte and Brunner (2024). In order to test whether we capture droughts and floods that correspond to the case study events, we allow a buffer window of +-five days on either side of the reported flood event. This buffer is to accommodate discrepancies between the media reporting timing and precise location of the events and the hydrological response in the data. For droughts, we do not allow a buffer period, but consider a drought to be detected if it overlaps with the media reported drought period.

2.3.3 Methods comparison

We compare the different threshold level methods and assess how the detected events differ. In the first instance, we consider whether or not the case study drought and flood events, i.e. those reported in the media, are detected, and secondarily whether or not they are considered a "transition" event. Then, we compare the threshold level methods for the entire streamflow time series, and, taking into account the hydrological regime types, analyze potential differences in the detection of transition events. We consider how the events detected by different threshold level methods result in different event characteristics across all events in the case study catchments. We focus here primarily on the timing of events.

Second, we consider how setting a top-down definition of the time intervals between drought and flood events may affect the analysis. (1) We begin by calculating the time interval between each drought event and the first subsequent flood event, resulting in a series of time interval values for each catchment. (2) Next, we fit a GEV distribution to the time interval data series using the R package *extRemes* and use the GEV parameters to compute the cumulative distribution function (CDF) for a theoretical period of 0-730 days (2 years). Several candidate distributions were tested, and it was shown that the GEV distribution was a good fit (based on the Kolmogorov-Smirnov and Anderson-Darling tests, for all case study catchments). This step is necessary because the events are sometimes unevenly distributed or too sparse to reliably estimate the probabilities of rare time intervals from the empirical distribution directly, and for some catchments, 14 days represents a fairly improbable transition time. (3) From the CDF for each catchment, we extract the probability of 14- and 90-day transition periods.

2.4 Qualitative assessment

Finally, we visually examine the time series of the case study catchments to explore what different event characteristics mean in context. The motivation for studying drought to flood transitions ranges from changes in physical processes, like soil water repellency resulting from dry periods, to water management or infrastructural concerns, like reservoir operations (Hammond et al., 2025). In this manuscript, we are interested in understanding and contextualizing which methodological approaches will result in the detection of transitions that are likely to have certain impacts, or which result from process changes that can be meaningfully interpreted in the desired context. Following visual inspection, we provide examples and demonstrate potential pitfalls in the typical event detection approaches. From this, we aim to offer recommendations for future event detection strategies.

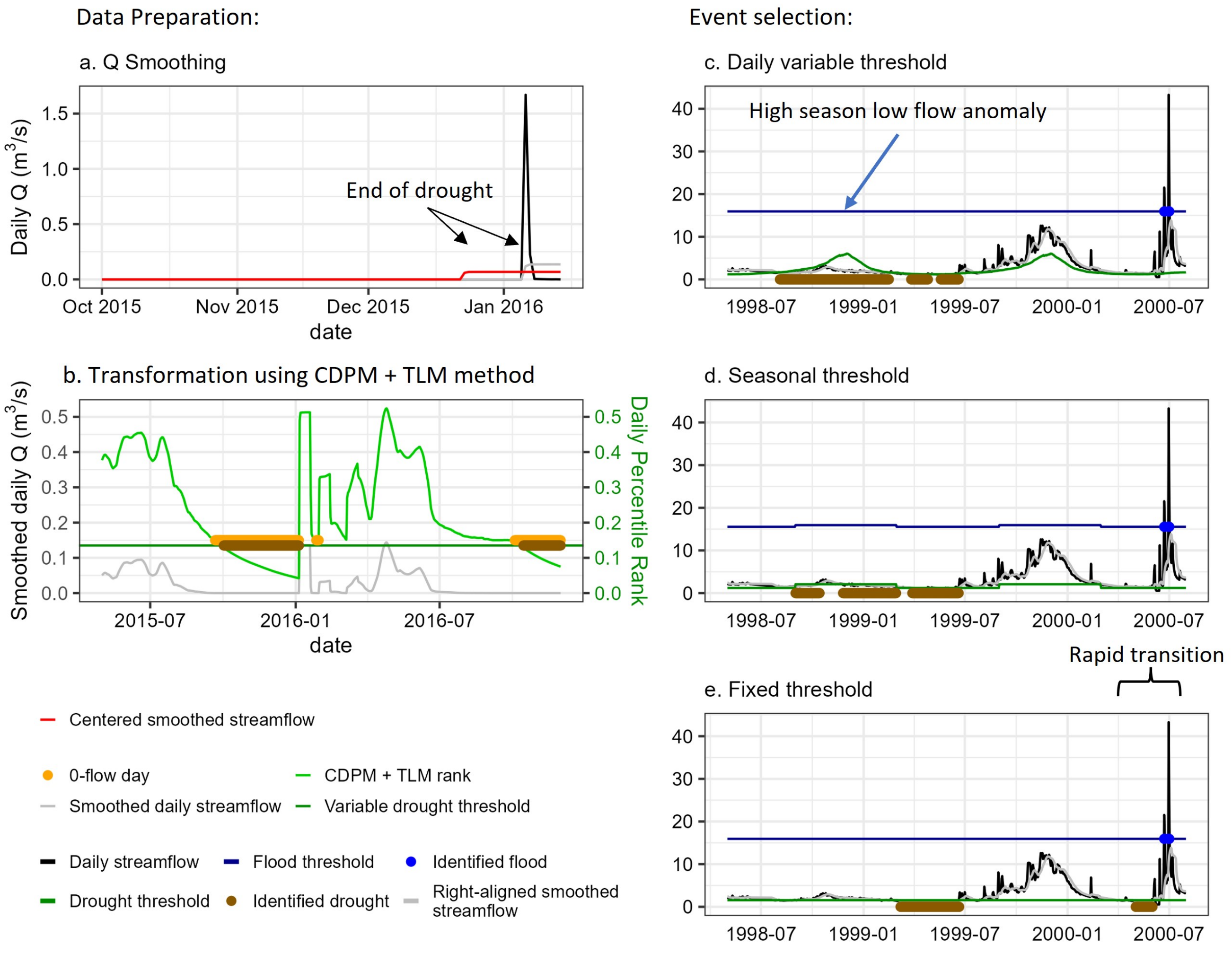

Figure 2. Methodology in brief: The first column shows the data preparation phase in which streamflow is smoothed (a.) and converted to percentiles for drought detection using the combined CDPM and TLM methods (b.). The second column shows the event selection process in which the threshold levels and the transitions time intervals are applied. Specifically, panel a. shows an example of the streamflow smoothing approach used for the detection of drought periods, demonstrating how a center-aligned smoothing window would result in an early drought end date as compared to a right-aligned window, as used here. Panel b. gives an example of the combined CDPM + TLM methods used for the smoothing and setting of drought thresholds in intermittent streams. Here, the threshold is represented by the corresponding ranked percentiles on the right y-axis, while the smoothed daily flow is in the original units on the left y-axis. Both panels a and b are examples from the catchment in California. Panels c, d, and e, show daily variable, seasonal, and fixed thresholds for drought respectively, and fixed (c. and e.) and seasonal (d.) thresholds for flood. Panel e demonstrates a rapid transition between drought and flood as detailed in the text. Panels c, d, and e are examples from the Chilean catchment. In these panels, the thresholds are shown relative to the original streamflow values, rather than relative to the ranked percentiles (as in b.), to facilitate visualization.

3 Results

3.1 Quantitative assessment

3.1.1 Detection of case study events

In the first instance, we examine whether the applied event detection methods are successful in detecting the case study drought and flood events. Overall, drought-to-flood transition events were not consistently detected for the reported periods (Figure 3). For one of the eight cases, we do not detect the drought event at all. For an additional 3 catchments we do not detect a drought in the reported period using one or two of the methods. For four of the eight cases, we detect a drought in the reported drought period using every method.

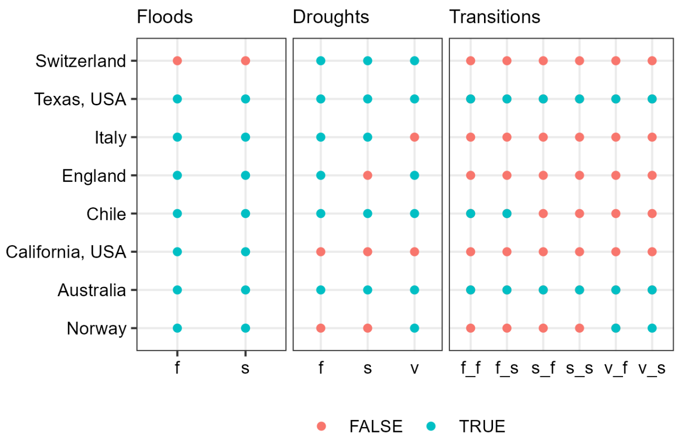

Figure 3. Summary of case study event detection across sites and methodologies. "True" indicates that an event was detected during the reported period. Threshold level method names are abbreviated as daily variable (v), seasonal (s), and fixed (f), and combinations used for transition detection are labeled with the drought method followed by the flood method (e.g. "f_s" corresponds to a fixed drought threshold and a seasonal flood threshold definition).

Detected drought events often only partially overlap with the reported-drought periods. Using the Emme catchment as an example, we found that each threshold level method detected a drought event some time during the reported-drought period (Figure 4.a., Table 1). However, none of the detected events spanned the full reported-drought period (January 2022-December 2022 for the Emme), and instead occurred over the course of several months between May and September, depending on the methodology. Detected drought events are often very short relative to the reported drought periods, or are detected as multiple shorter drought events (ex. Figure 4.a.). Thus, if, for instance, the reported drought event is one-year long, and the detected hydrological drought is only one-month long, this would still be considered to have been captured by the method.

A similar result is visible in the time series of the Savio River in Italy (Figure 5). Here, only the fixed threshold and the seasonally fixed threshold detect drought events during the reported-drought period (i.e., during the low flow season in Summer 2022, despite noticeably lower than typical streamflow throughout the 2022 and early 2023 hydrological years). This case is presented here for the complete time series, which demonstrates the severity of the 2023 flood, and the relatively dry preceding streamflow conditions. The results in the River Savio suggest that the drought threshold levels used in this analysis may be too strict. Second, these results show a concentration of drought events in the early years of the time series (Figure 5.a.), suggesting that the detection of transition events are sensitive to the length of the time series.

Flood events are detected, regardless of the threshold level method, for all catchments except for the Swiss case study. The reported flood event at this location was not detected by either threshold type using the daily mean streamflow data (Figure 4.a.). However, given data availability and the understanding that this is a flashy regime (Table S1), we also examined the hourly streamflow time series for this catchment. Although the peak daily mean flow (17 m^3/s) on the date of the case study flood did not represent an extreme flood, the hourly streamflow peak (255 m^3/s corresponding to the 99.99^{th} percentile of daily maximum time series) far exceeded the flood threshold . In this example,the transition from low flow, to flood, and back to low flow condition in the river occurred within less than 12 hours, so the daily mean flow was not able to capture the extreme flood event (Figure 4.b.).

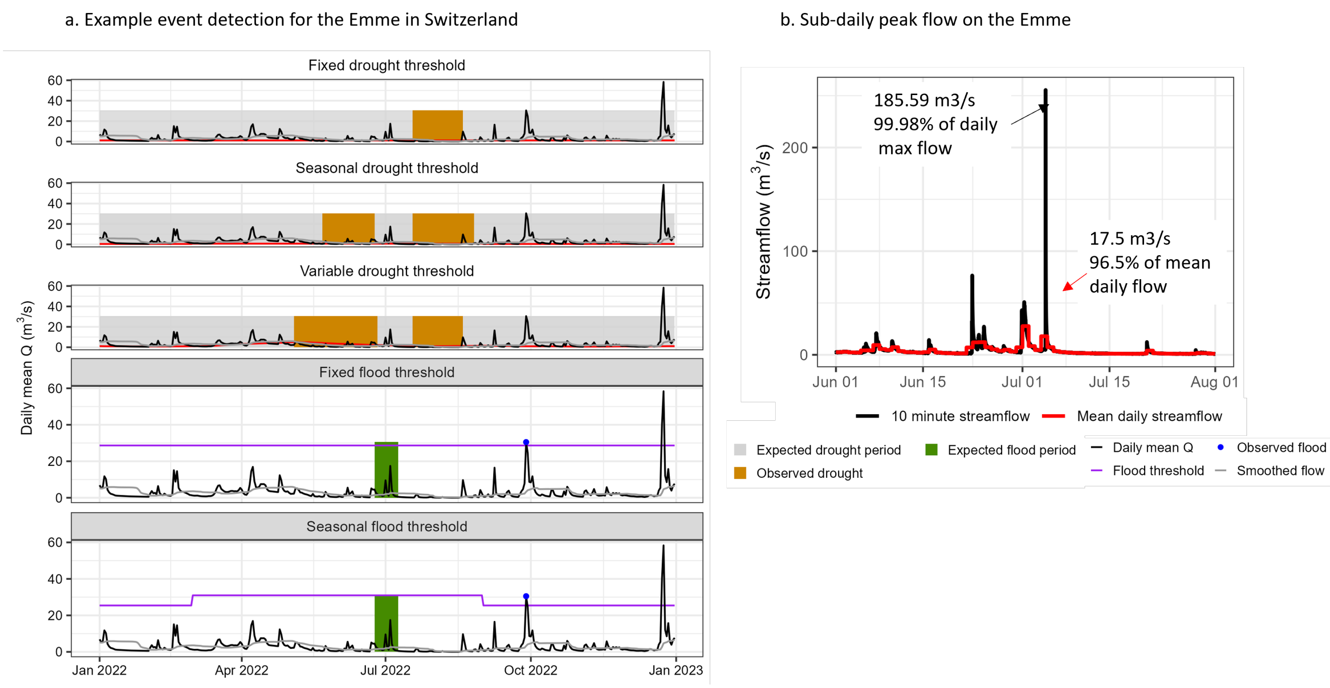

Figure 4. Detection of case study events. Panel a. shows an example (Emme River in Switzerland) illustrating the detected drought events during the case study period, while no flood was detected on the reported date. Panel b. shows how the flood peak for the case study event on the Emme differs between the daily mean and sub-daily/hourly) streamflow time series.

In combination, we do not detect transitions for four out of eight sites (Switzerland, England, Italy, and California), regardless of methodology. In Texas and Australia, however, the case study transition is detected by every threshold level combination. In both cases, a large, sudden, precipitation-driven flood followed a drought period in the low flow season. In the Chilean case study, a transition is only detected when the fixed threshold is used, however, this event actually falls outside of the reported drought period (Figure 2.e.). In this case, the time interval between the reported drought period and the flood period was larger than 90 days, implying that it would not have been considered given a predefined temporal lag of 90 days as used here. Finally, for the Norwegian case study (Figure 5.b.), the transition is only detected when a variable drought threshold is used. The other methodologies do not detect anomalously low flow (i.e., lower than normal flow) outside the typical low flow season, whether in the summer or winter season, as drought. The flood event, driven by a combination of snowmelt and rainfall, was detected by both approaches.

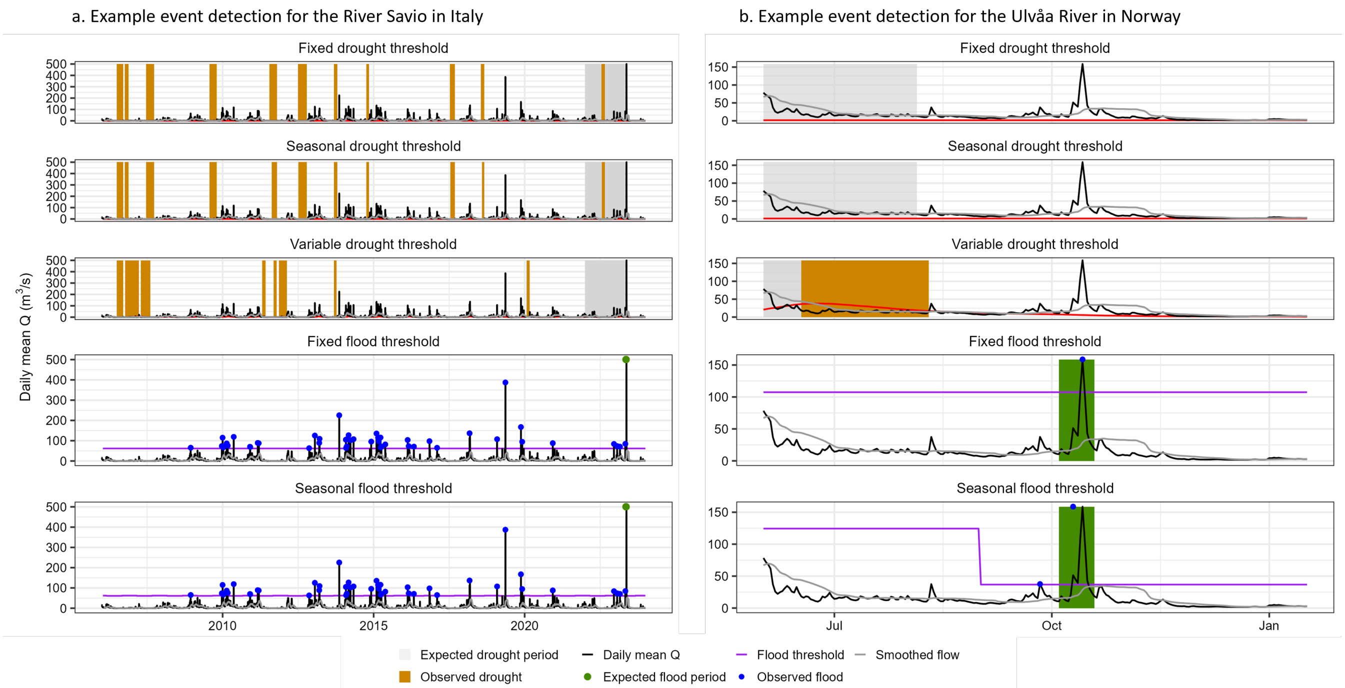

Figure 5. Detection of case study events in a. the River Savio in Italy, here shown together with the complete available streamflow timeseries, and b. the Ulvåa River in Norway shown here for the 2018 case study event only.

3.1.2 The choice of threshold level method affects detection of transitions

When considering the entire streamflow timeseries, rather than just the case study events, the number of detected transition events varies greatly across the eight case study catchments and different combinations of threshold level approaches (Figure 6). In the catchments with marked seasonality (Norway, Australia), we generally see an increase in the number of events when a seasonal, as opposed to annual, flood threshold is used. In highly seasonal catchments, the combination of the flood and drought threshold level methods play a major role in determining the number of events detected.

In catchments with moderately strong seasonality and a pluvial (California, England) or mixed regime type (Chile, Italy), differences in the detection of transition events appear to be more strongly related to the drought threshold level method (Figure

6). The Chilean catchment experiences a pronounced dry season often followed sharply by rainfall driven flood season prior to the snowmelt period (Figure 1; Table 1). Here, we see that more variable drought threshold level methods (v and s) result in a reduction in the number of transition events, similar to the Italian catchment (Figure 6). For the English catchment, we see the inverse: increasingly variable drought threshold level methods result in increased numbers of transition events. This is not surprising considering the regime characteristics, as floods typically occur in the middle of the high flow season, and thus, drought detection during the high flow season will increase transition occurrence. Finally, in the catchments with very low seasonality (Switzerland and Texas), we find that the number of transition events is high overall (in the Swiss case, around one transition every two years). Allowing for variation in the flood threshold level has the largest apparent influence on event detection. Overall, the choice of threshold level methods appears to be less important in these cases.

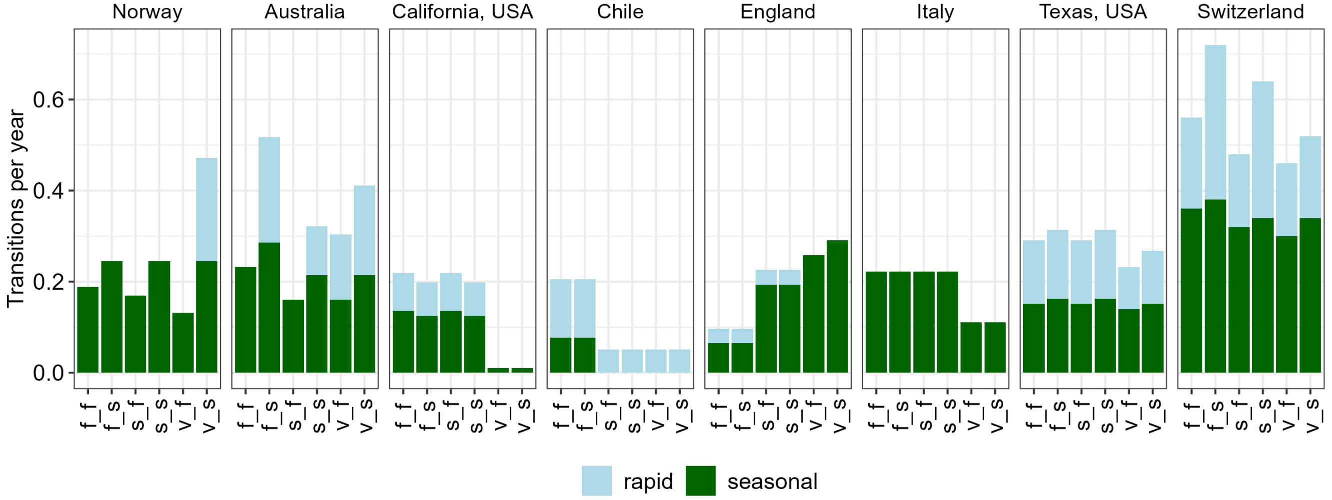

Figure 6. Number of drought-to-flood transition events per year (y-axis) detected in the complete time series for the eight case study catchments. The x axis shows the different threshold approach combinations, where the first letter represents the threshold level approach for drought, and second, the threshold level approach for floods, as previously.

In the Californian catchment, which experiences intermittent flow in the dry season followed by a pronounced wet season in winter, a variable drought threshold (using the combined CDPM + TLM method) detects very few transition events because the latter part of the dry season typically experiences zero-flow (Figure 7). Although the intention of the combined CDPM + TLM method is to allow for the detection of hydrological drought in intermittent rivers (van Huijgevoort et al., 2012), this still presents a problem here. The method performs well with fixed annual (Figure 2.b.) and seasonal thresholds. However, when a variable threshold is applied, each streamflow day is compared to normal conditions at that time of the year. Thus, while the method represents an improvement for intermittent and ephemeral rivers as compared to threshold level methods alone, the use of a daily varying smoothed threshold may mean that the start of the zero-flow period is not be considered to be a drought if dry conditions are typical in the rolling-window (Figure 7). This may pose a problem for the detection of transition events at the end of the zero-flow season if a daily variable threshold is applied.

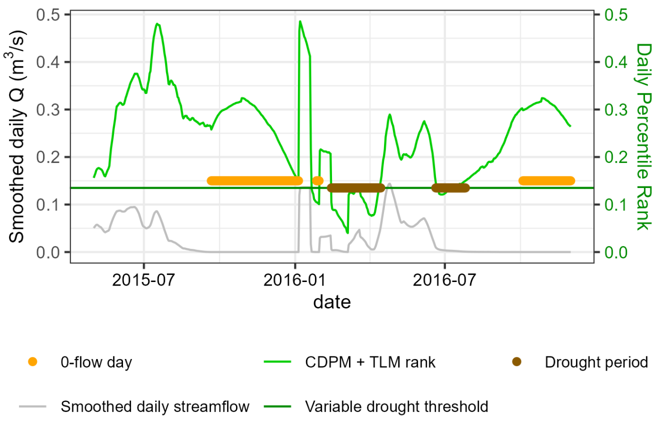

Figure 7. Drought detection using the combined CDPM + TLM method using a daily varying threshold for the intermittent Ventura River in California, USA. Here the threshold is represented by the corresponding percentiles on the right y-axis, while the smoothed daily flow is in original units on the left y-axis. Note that in the zero-flow periods in summer 2016, the method does not detect drought, since the duration of the zero-flow period is not below the percentile threshold for the rolling window period, as opposed to the same approach applied with a fixed 2 or seasonally fixed threshold.

The different threshold level methods result in highly varied responses in seasonal catchments. This variation is explained by the way in which the threshold levels are calculated. Using a daily varying threshold (v) for drought, for example, in a highly seasonal catchment, would result in a relatively high low-flow threshold in the high flow season. Thus, one may select a drought in the high flow season given that the flow is significantly lower than normal (high) flow value, which may not be considered to be a drought by some, as it does not necessarily imply absolute low water levels. Rather, the flow is an anomaly as compared to the normal flow for the time of the year.

Using a fixed seasonal threshold (s: one for summer and one for winter) in catchments with two pronounced low flow seasons, allows drought events to be selected in both summer and winter. In these catchments one may identify a higher number of drought-to-flood transitions given that flood occurs in both seasons. Using a fixed threshold (f: based on a percentile from the whole series) will only select drought events in the dominating low flow season, ensuring that real drought events in absolute low flow terms are identified. However, if the lowest flows occur in winter and the interest lies in summer low flows, a seasonal threshold is preferable.

3.1.3 Choice of event detection method affects event seasonality and characteristics

Individual flood and drought events, whether or not they comprise a transition, exhibit different characteristics depending on the choice of threshold level method. Notably, the timing of events varies substantially between methodologies and streamflow regimes (Figure 8.a.). For example, fixed thresholds result in a relatively consistent timing of the onset and end of drought in a majority of locations (Figure 8.a.). With increasing variability in the threshold definition (s, v), the variability of detected drought timing also increases. Fixed thresholds, in flow regimes with a seasonal signal, will generally detect drought in the low flow season, but variable thresholds (including seasonal) will allow the detection of low streamflow anomalies even during high flow seasons. To some extent, the same types of seasonal patterns can be seen for floods, although most of the case study catchments exhibit similar flood seasonality for both methodological approaches (Figure 8).

Thus, these different threshold types may result in the detection of different types of flood and drought events. Fixed thresholds will detect those which are more in line with the seasonal norms, e.g. flood events which occur during the high flow season and droughts which occur during the low flow season. These events are more likely to be driven by larger scale processes, for example, drought periods driven by cold winter weather or floods driven by snow melt in the spring, although very severe events would be detected outside of seasonal patterns. In contrast, variable thresholds are sensitive to anomalies within a season. This means they can capture atypical events, which may not necessarily be large in terms of absolute magnitude, for example, droughts during typically wet periods which may be indicative of short-term rainfall deficits or a delay in the snow melt season, for example. Floods events during drier periods potentially driven by intense, short-duration rainfall which does not result in a large absolute magnitude of flow, could also be detected. In other words, variable thresholds may detect events which are not extreme in an absolute sense, but which are anomalous in a specific time of year. In regimes which do not have a strong seasonal cycle, the threshold choices should not result in the detection of substantially different events.

The timing of drought-to-flood transition events does not vary as systematically between methodologies as the events do separately (Figure 8.a.). The catchments which show highly seasonal flood timing regardless of methodological approach also have relatively consistent transition timing. This suggests that the flood timing is a determining factor in whether or not a transition occurs. There are some exceptions to this. For instance, the Chilean catchment experiences transitions in the first 100 days of the hydrologic year, relatively consistently across methodologies, despite inconsistent flood timing (Figure 8.a.). In this case, the time at which droughts end is a primary control. In the Texas and Switzerland case study catchments, transitions are widely dispersed throughout the year regardless of the approach.

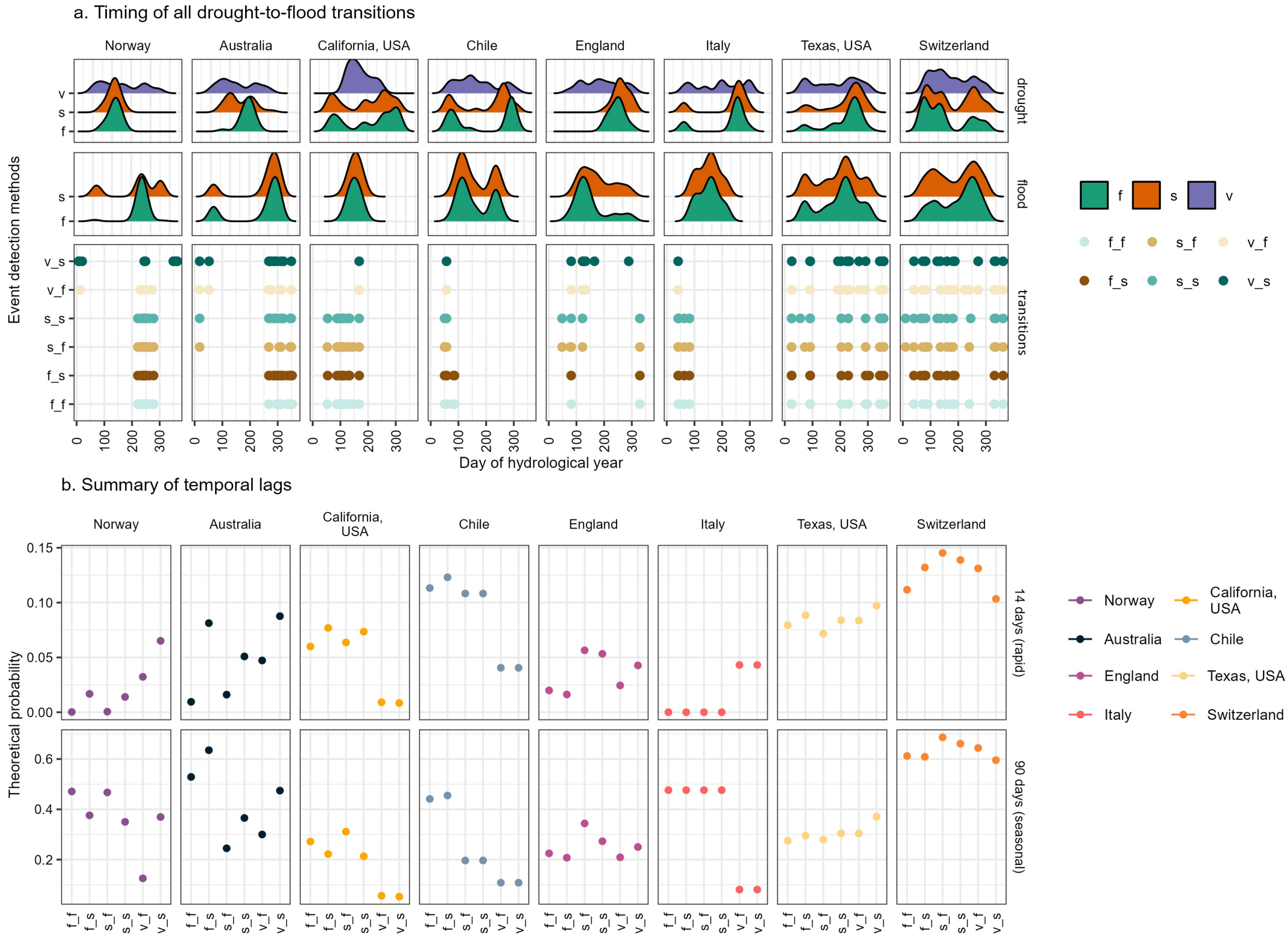

Figure 8. a. Timing of drought (first row), flood (second row) and transitions events, defined as the start date for the flood event (last row), detected using different threshold approaches for the eight case study catchments (columns). The day of the hydrological year is on the x axis, where the first of April is day one in the southern hemisphere and October first is day one in the northern hemisphere. Threshold level method names are abbreviated as daily variable (v), seasonal (s), and fixed (f). As above, for the transition timing panel, the drought threshold level method is first, and the flood method is second, so that the abbreviation represents the combined approach. The catchments are ordered from highly seasonal regimes on the left to highly variable regimes on the right. b. Summary of the 5th percentile of lag time between drought end date and flood start date when defined probabilistically. Here the error bars represent the 95% empirical confidence interval of the resampled distribution.

In this analysis, we used the approach of Götte and Brunner (2024) in which transitions are universally considered to be "rapid" if the flood starts within 14-days of streamflow crossing the drought threshold, and " seasonal" if this transition occurs within 90-days. This top-down selection of a time interval between events impacts the detection of transitions, especially since different methods can result in different drought end dates, thus potentially excluding events from being defined as transitions if the end date is shifted by a few days.

Here, we tested an alternative approach in which the time intervals between all drought events and the first subsequent flood period were defined probabilistically in each catchment (Figure 8.b.). The results indicate that, depending on the methodological approach and the flow regime, the probability of a transition can vary widely. For example, in the Norwegian case, the probability of a 14-day time interval between the end of drought and start of flood ranges from 0.02% when fixed thresholds are used (f_f), to 6.5% when variable thresholds are used (v_s). On the other end, the probability of a transition within 14 days in the Swiss case study catchment reaches as high as 14.5% (s_f) and has greater than a 10% chance of occurrence within this time window, regardless of the approach. These results show that the few transitions identified within the selected time windows may differ substantially among the case study catchments, which point to the need for more research on how to best define robust and meaningful transition schemes for hydrological extremes.

3.2 Qualitative assessment

The qualitative assessment of the streamflow time series reveals that challenges with the threshold method approaches are most pronounced for regimes with a strong seasonality. In these cases, a variable threshold takes on different values throughout the year and thus corresponds to different hydrologic conditions, including high and low flow seasons. In other words, different approaches may not select events that exhibit the same traits or carry the same impacts. Accordingly, studies focusing on different impacts may require different definitions as each definition emphasizes certain aspects of droughts and floods.

Drought events, especially those detected by a variable threshold, may or may not correspond to dry soils or reduced water availability in catchments, notable where streamflow has a defined seasonality. In seasonal regimes, droughts may be detected in the high flow season if streamflow is lower than normal. For example, in the Australian catchment, droughts can be detected during the monsoon season (Amale et al., 2023). Although such events are representative of anomalous seasonal flows, they are unlikely to represent low flows from an annual perspective, i.e., they may not correspond to an absolute water deficit.

In catchments with highly seasonal flow, variable drought thresholds could potentially also result in the detection of droughts resulting from a delay in the onset of the high flow season as seen in 1990 in the Daintree River in Australia (Figure 9.a.). Here, the detected drought event may be caused by a delay in the onset of the monsoon season, which, when followed by a typical, or even above average wet season, as is the case here, may result in drought-like impacts, or may not, depending on the context. For example, monsoonal delay could have significant impacts for agriculture as the dry season is prolonged (Amale et al., 2023; Lisonbee et al., 2020; Fitzpatrick et al., 2015). On the other hand, in snow-dominated catchments when, for instance, a particularly cold winter is followed by a delayed, but otherwise typical snowmelt season, this may also result in the detection of drought by variable threshold level methods which may then be followed by a typical flood (Brunner et al., 2023). While such events may have impacts on industry, whether or not these represent important transition events is unclear. On the other hand, fixed thresholds will favor drought periods in which streamflow is low relative to the flow regime, and, as such, correspond to dry conditions in absolute terms. Although these events may represent absolute streamflow deficits, they may also represent somewhat normal conditions if the threshold is not low enough. For example, identifying the low flow period as a drought may be misleading in catchments where low flow periods always occur during the same time of the year (e.g. winter in snow-rich regions). If a fixed threshold is too low or does not accommodate the possibility of a secondary low flow season (e.g. summer), in a seasonal regime, droughts that occur outside of the primary low flow season may be missed. This is demonstrated in the 2018 case study example in Norway (Figure 9.c.,d.), where an early and reduced melt season and high temperatures resulted in a summer drought (Bakke et al., 2020), although the event was not severe in the selected catchment. Here, the fixed threshold method failed to capture a drought that occurred at the end of the snowmelt season (summer 2018), and as a consequence, did not capture the transition event. Missing drought periods outside of the low flow season could result in failure to detect meaningful transitions driven by anomalous weather events, such as the heavy rainfall, high temperatures, and seasonally atypical snowmelt timing that resulted in detecting a drought event in the Norwegian case.

In the Norwegian and Australian examples (Figure 9), the transition event is best detected by the variable threshold level approach for drought. However, the challenges of event detection in highly seasonal regimes are not solved by merely using a fixed, or seasonal, threshold approach. Whether the detected transitions are impactful would depend on the sector of interest. For drought-to-flood transitions research to be informative, the drivers and the impacts of interest should be considered. To extend the previous example, in seasonal snow climates, such as in Norway, it is common to distinguish between winter and summer low flows, both of which may be of potential interest and have potential impacts. For example, a winter low flow is typically caused by very low temperatures. It may limit subsurface flow to groundwater wells or rivers, and thus impact local water supply. It is important to separate between the two kinds of low flow events (winter and summer in this case) as they are generated by different processes (Tallaksen and Hisdal, 1997). Thus, the problem of event detection in the low flow season could be mitigated by considering the event types, and seasons, separately – deriving separate thresholds for each season. Similarly, it may be reasonable to assume that in wet climates, low anomalies in the high flow season may not be impactful, while in dry climates, these events may have a greater impact. These examples highlight the need for consideration of drivers and impacts when researching drought-to-flood transition events.

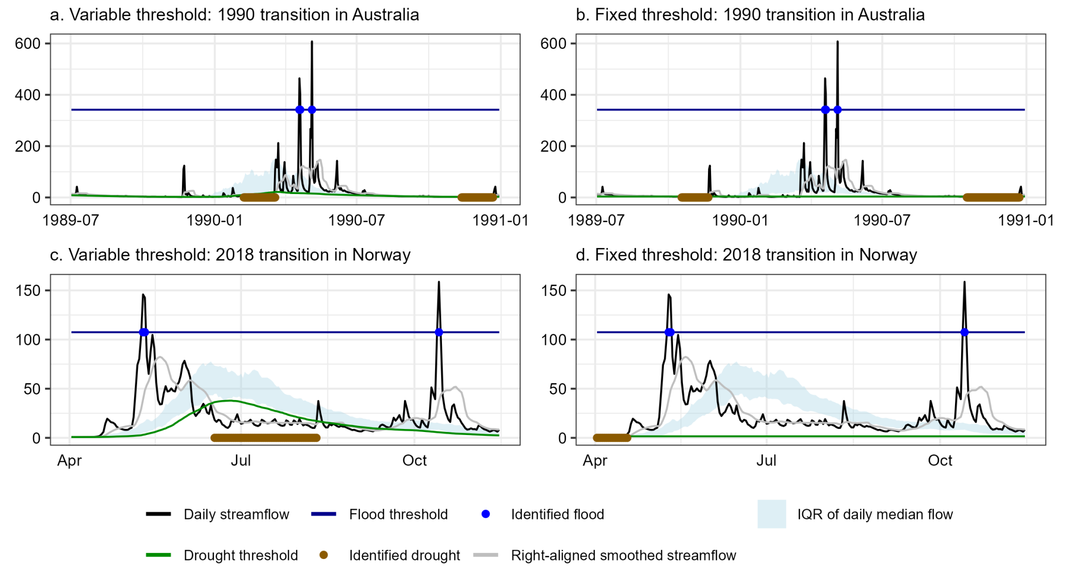

Figure 9. Examples showing differences in drought-to-flood transitions in highly seasonal regimes, where (a.) shows a drought event caused by a delay in the onset of the monsoon season in Australia as detected by a variable threshold, but not by a fixed threshold (b.). In this case, the "area under the curve" of flow volume in the high flow season was above average (7789 between 15/12/1989 and 15/08/1990 vs. the median of 6201. (c. and d.) show the case study event in Norway. In this example the variable threshold detects drought at the end of the snowmelt season, while a fixed annual threshold misses the event. Streamflow values on the y-axis are in m^3/s

In catchments with a limited seasonal cycle, the difference between threshold level approaches is of marginal, if any, importance. However, it is worth noting that in catchments that react quickly to precipitation events, as in the Texas and Switzerland case studies, and in catchments that experience a pronounced dry and rainy season, such as in the cases of Australia and California, the normal condition can be one of dramatic swings between low and high flow conditions. In these cases, very dry conditions may not be highlighted as drought, especially when a variable threshold is used, if the average condition at that time of year is dry or if dry periods are short and punctuated. Transitions detected in such cases may represent a magnification or acceleration of a normal pattern of wetting and drying cycles as the most extreme examples of the normal pattern will be selected.

4 Discussion and recommendations

4.1 Event detection challenges

The results of the quantitative and qualitative analyses highlight that different types of drought-to-flood transition events bring their own challenges. These challenges primarily relate to the need to adapt the methodology to the impacts or physical processes that drive interest in drought-to-flood transition events, in order to avoid detecting events that do not have the intended characteristics.

4.1.1 Challenges with drought detection

Selecting appropriate threshold level approaches for drought detection can be particularly difficult. Variable thresholds for drought may be most appropriate for use in drought-to-flood transitions research in cases when it is not important that a catchment be ’dry’ in an absolute sense. For example, rapid changes between anomalously low and high flows, regardless of the absolute amount of water in a catchment, could present significant management problems for e.g., water quality or environmental flows. In the Italian case study catchment, cycles of low and high streamflow can increase eutrophication, a concern in the Adriatic Sea into which the Savio River flows (Sani et al., 2024), and fish health can be effected by rapid shifts in hydrologic condition (Ceola et al., 2018). Similarly, hydropower production through run-of-the-river power plants may be sensitive to deviations from typical conditions because these rely on the natural flow of a river (Schaefli, 2015). Thus, lower than normal winter low flows in a snow-driven alpine catchment could result in a reduction in hydropower generation from such plants. Deviations from the average condition could therefore be impactful, while the identification of the low flow season, as might be detected using a fixed threshold, may not be.

Fixed thresholds and seasonal thresholds, on the other hand, may be appropriate in a transitions context when the primary concerns are the detection of longer drought periods, or periods in which soil and river flow conditions are "dry" in absolute terms. Hazards that relate to changes in soil properties may be more closely linked to dry conditions. For example, the occurrence of dry spells followed by heavy rainfall has been shown to lead to an increase in landslide occurrence (Tichavský et al., 2019), and wet/dry cycling can lead to increases in soil erosion (Weng et al., 2024; AghaKouchak et al., 2020) and degradation (Ye et al., 2011). Earthen structures and levees may be more likely to fail as a result of switches between drought, corresponding to an absolute deficit of water, and flood events (Robinson and Vahedifard, 2016; Ward et al., 2020; Janga et al., 2024). Serious water quality issues resulting from the build up of toxic materials in sediments that are washed away by subsequent rainfall may also occur (Schönbrunner et al., 2012; Lisboa et al., 2020). For example, the River Aire, in England, is an industrialized catchment in which heavy metals from industry and contaminated road dust are accumulated in sediments during the low flow season and mobilized at high concentrations in streamflow, rather than being diluted, during high flow events (Carter et al., 2006). Finally, if concerns are primarily around the likelihood of increased runoff from precipitation events due to soil hydrophobicity, prolonged drought periods accompanied by absolutely dry conditions may be most appropriate.

4.1.2 Challenges with flood detection

In general, the definition of floods in the context of drought-to-flood transitions as defined here appears somewhat more straight forward compared to the definition of drought. The primary challenge appears to be the selection of threshold levels. The selection of threshold level, in itself, is not, however, a trivial matter.

For example, according to the media-reports, the 2022 drought event, which affected the Emme River in Switzerland was severe and had wide reaching impacts (Table 1). The subsequent flood event was also extreme (Table 1). Our analysis of the sub-daily data on the Emme River in Switzerland suggested that rapid floods, like those that are driven by short rain events, may be entirely missed using daily mean streamflow, as also demonstrated by previous research (Bartens et al., 2024). In line with the results of Barendrecht et al. (2024), this could be problematic, as many floods that follow drought may be "flashy" in character and driven by high intensity rainfall, especially for rapid transition events. Given that sub-daily, or instantaneous peak streamflow is not available in most catchments globally (Fill and Steiner, 2003; Bartens et al., 2024; Ding et al., 2014), it may suffice to use lower flood thresholds applied to daily mean streamflow in transition studies.

Lower thresholds, however, may still result in some events being excluded and less impactful events may be included. This calls to attention the need for increased research into how and when droughts magnify the impacts of flood events. To adequately capture rapid drought-to-flood events at a global scale, alternative methodologies should be explored, and flood drivers, event-based approaches, and higher temporal resolution precipitation series should be considered. Finally, as an aside, although we have only considered flood as an absolute high flow over a fixed (or seasonally fixed) threshold, it is possible that rapid fluctuations between wet and dry conditions regardless of the magnitude of the events could be meaningful in some contexts (e.g. for run-of-the river hydropower generation, or ecological health).

4.1.3 Challenges with transitions detection

In addition to the previously discussed pitfalls and concerns with adequately capturing the impacts of interest in transition research, it is clear that current methodologies may fail to capture transition events that have been impactful in the real world. This is demonstrated by our analysis of the case study events in which the transitions were only consistently detected (using all methodological approaches) for two catchments (Texas and Australia). In some cases, failure to detect transitions appears to be due to a failure to detect drought and flood events individually. In others, it is more likely due to the challenge of defining an appropriate, catchment specific, time interval between events (Figure 8.b.). This effect is critical because the end date of the drought event can be highly variable when different threshold types and levels are used, thus extending this "lag" between events.

In summary, when designing a study that incorporates many regime types, it is important to consider the drivers and characteristics of drought and flood events so that the main physical processes are represented. Further, it may also be pertinent to explicitly consider the impacts or sectors that are of interest. What is impactful in one sector may have no effect in another. The most appropriate definition will always depend on the application of interest, and this should be made explicit in research related to rapid transitions between drought and flood. When considering hydrological extreme events, and transitions in particular, the actual impacts can be extremely context dependent. For instance, a transition identified using one method may be considered impactful for one country or sector but not for another, where similar events may not even be regarded. Similarly, a drought-to-flood event could have significant impacts in locations with higher socio-economic, infrastructural or ecosystem vulnerability, even if the time interval between the two hydrological anomalies far exceeds the seasonal window applied thus far. In contrast, the same event (in terms of magnitude or rate of change) may not qualify as a transition in a less vulnerable location where the recovery process between the end of a drought and start of a flood is faster. In this sense, the definition of drought-to-flood transitions would benefit from a more location specific approach.

4.2 Methods need to be adapted for transitions

To some extent, different threshold level types can be chosen so that they are appropriate to the impacts of interest. However, many impacts could be sufficiently (or insufficiently) represented by any of the tested approaches. The methodologies evaluated in this study could be further modified and new methodologies could be developed to better capture and characterize drought-to-flood transitions for different regimes.

One approach could be to apply a secondary filtering step after the initial event selection process. For instance, one could apply a variable drought threshold and then filter to only retain those events representing drought conditions that meet certain criteria. For example, droughts that occur in the snowmelt season in snow dominated catchments could be removed, focusing on summer drought events. Explicitly considering the drivers of drought and flood events, or at a minimum, filtering for the seasonality could bypass some potential pitfalls and allow for a more deliberate selection of events.

Another possible approach is to consider time intervals between drought and flood events, as well as the magnitude of shifts between low and high flow probabilistically. Generally, communities and industry that exist in close proximity to rivers have adapted to the normal conditions of that river (Di Baldassarre et al., 2015). In other words, hydrological events that would be considered extreme in some locations may be un-impactful in others. Further, although droughts and floods that comprise transition events are not individually extreme, their combined effects may be both statistically rare and/or particularly harmful (Zscheischler et al., 2020; Tilloy et al., 2019; Liu et al., 2016a).

Thus, when defining hydrological transitions, one possible option to avoid applying arbitrary thresholds or time intervals across many catchments, may be to probabilistically define parameters of the methodology relative to the normal condition of individual or geographically proximate rivers. For time intervals, this could involve a similar process to that presented in Figure 8.b. Changes in magnitude could also be defined probabilistically. For instance, if large swings between low and high flows are typical, high magnitude changes may be needed to warrant consideration. Although a probabilistic approach would not be explicitly tied to impacts or physical processes, such approaches would allow events to be defined relative to normal conditions within a catchment. In this way, analyses could take into consideration the relative rarity of drought-to-flood transitions as combined events.

4.3 Limitations

Although this analysis is intended to compare methodological approaches for the detection of streamflow droughts and floods in the context of drought-to-flood transitions, it is necessary to make some choices in regards to the methodologies applied. The threshold levels and approaches used, minimum time periods and aggregation and smoothing windows applied, may all have some effect on the type, timing and presence of transition events detected. Other choices, such as the 30-day minimum drought duration, or the decision to merge drought periods with less than 15 days apart are somewhat arbitrary. These choices were made based on existing literature to facilitate comparison in a consistent framework. Further, while focusing on original daily data series, standardized indices may be appropriate when switches between longer dry and wet periods, rather than individual events, are of interest.

In the literature to date, “drought to flood transition” has been used as a general term and different definitions and methods have been used to define the events as well as their transition (from drought to flood). The definitions of drought to flood transitions explored here do not address, in detail, how different drought types e.g. meteorological or soil moisture would fit into this framework. This is not relevant to our study because we focus on streamflow conditions. Neither do we address how different durations, intensities or severity of drought or flood would play into this dynamic relationship. Long-term droughts are likely to have a very different relationship with floods than short, or less severe, events, for example. Understanding how individual event characteristics influence transition occurrence represents a key area for further research.

Further, the selection of case study events is here based on streamflow magnitude, whereas media reports may mix event types (e.g. hydrological and meteorological drought), and the impacts can be wide-ranging. Additionally, the streamflow time series in some catchments (e.g. the Chilean case study) can have quality issues, such as data gaps, which often occur during periods of extremely high flows. This is not a problem specific to transitions, because it affects the calculation of any flood statistics, however, this could introduce biases in the selection of flood events. Short streamflow time series and data quality issues (such as missing data on high flow days in the Chilean case study catchment) could affect the accuracy of the thresholds used for drought and flood definition. The use of fixed or variable threshold analysis on short time series may not capture the full range of variability in the streamflow as compared to longer time series. However, this effect would apply consistently across all approaches and methodological combinations (fixed and variable thresholds, for both drought and flood detection), thus limiting the extent to which this influences the outcome of this analysis. Despite these challenges, the case studies provide a unique dataset covering a wide range of regimes necessary to understand the pro et cons of the methodologies and how their choice can influence the detection, or failure to detect, known and important drought-to-flood transition events.

5 Conclusions

In this paper, we have analyzed eight catchments that have experienced real-world impacts from drought-to-flood transitions. For these catchments, we have assessed the suitability of, and differences between, threshold level approaches for drought and flood detection in a transition context. We have demonstrated that different threshold level approaches can result in the selection of different drought and flood events individually, and that when combined, this can influence the number and seasonality of detected transition events.

Further, we have shown that despite reported impacts, many of the case study events were not detected as transitions. This implies that there is a problem with the existing approaches in some contexts. We demonstrate that in some cases (e.g. the Emme in Switzerland), rapid floods caused by short rainfall events may be missed in daily time series or when high thresholds are used. We show that time intervals between drought end and flood start dates can differ substantially for the same events depending on the applied method, and we highlight the importance of selecting an appropriate time interval when defining drought-to-flood transitions. We further show that caution should be applied when choosing methodology to ensure that detected events have the desired characteristics.

There is currently no "one size fits all" approach to transition detection, instead, we recommend that future research into drought-to-flood transitions needs to be designed carefully, taking into account how definition and methodological choice can influence the type, characteristics, and potential impacts of detected drought-to-flood transitions. We suggest that some of the outlined pitfalls can be avoided by applying secondary filtering steps to select only events in a particular season or with certain drivers, by making efforts to specify the impacts that are of interest in an analysis, or by probabilistically defining transitions based on the dynamics of individual catchments. The physical characteristics of droughts defined using different approaches should be considered in the context of the specific impacts or physical process changes that are of interest. Finally, as a matter of priority, new methodologies should be developed that are designed to capture transitions jointly and further research is needed into how droughts and floods influence one another.

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