Drought Spatial Extent and Dependence Increase During Drought Propagation From the Atmosphere to the Hydrosphere

Journal Article

Author(s):
Brunner, Manuela; Chartier-Rescan, Corentin

Publication date:
2024-03-28

Permanent link:
https://doi.org/10.3929/ethz-b-000666867

Originally published in:
Geophysical Research Letters 51(6), https://doi.org/10.1029/2023GL107918

Geophysical Research Letters

RESEARCH LETTER
10.1029/2023GL107918

Key Points:

- Drought propagation affects local and regional drought characteristics and leads to longer, later, fewer, and larger droughts
- Only 20% of the precipitation deficits propagate to streamflow, while 40% of the streamflow deficits propagate to groundwater
- Spatial drought connectedness increases from precipitation to streamflow but decreases again for groundwater

Supporting Information:

Supporting Information may be found in the online version of this article.

Correspondence to:

M. I. Brunner,
manuela.brunner@env.ethz.ch

Citation:

Brunner, M. I., & Chartier-Rescan, C. (2024). Drought spatial extent and dependence increase during drought propagation from the atmosphere to the hydrosphere. *Geophysical Research Letters*, *51*, e2023GL107918. https://doi.org/10.1029/2023GL107918

Received 22 DEC 2023
Accepted 23 FEB 2024

Author Contributions:

Conceptualization: Manuela I. Brunner
Data curation: Corentin Chartier-Rescan
Formal analysis: Manuela I. Brunner
Funding acquisition: Manuela I. Brunner
Methodology: Manuela I. Brunner
Visualization: Manuela I. Brunner
Writing – original draft: Manuela I. Brunner
Writing – review & editing: Corentin Chartier-Rescan

Drought Spatial Extent and Dependence Increase During Drought Propagation From the Atmosphere to the Hydrosphere

Manuela I. Brunner[1,2,3] and Corentin Chartier-Rescan[1,2,3]

[1]Institute for Atmospheric and Climate Science, ETH Zurich, Zurich, Switzerland, [2]WSL Institute for Snow and Avalanche Research SLF, Davos Dorf, Switzerland, [3]Climate Change, Extremes and Natural Hazards in Alpine Regions Research Center CERC, Davos Dorf, Switzerland

Abstract As droughts propagate both in time and space, their impacts increase because of changes in drought properties. Because temporal and spatial drought propagation are mostly studied separately, it is yet unknown how drought spatial extent and connectedness change as droughts propagate though the hydrological cycle from precipitation to streamflow and groundwater. Here, we use a large-sample dataset of 70 catchments in Central Europe to study the propagation of local and spatial drought characteristics. We show that drought propagation leads to longer, later, and fewer droughts with larger spatial extents. 75% of the precipitation droughts propagate to P-ET, among these 20% propagate further to streamflow and 10% to groundwater. Of the streamflow droughts, 40% propagate to groundwater. Drought extent and dependence increase during drought propagation along the drought propagation pathway from precipitation to streamflow thanks to synchronizing effects of the land-surface but decreases again for groundwater because of sub-surface heterogeneity.

Plain Language Summary As rainfall deficits develop into discharge and groundwater deficits, the impacts of droughts increase. While we know that drought impacts and properties change during drought development, it is yet unknown how the spatial characteristics of droughts change over the duration of an event. Here, we use a large dataset of 70 watersheds in Central Europe to study the development of drought characteristics over the duration of a drought event. We show that drought development leads to longer, later, fewer, and larger droughts. 20% of the rainfall droughts develop into discharge droughts, and 10% into groundwater droughts. Of the discharge droughts, 40% develop into groundwater droughts. Drought extent increases during drought development from rainfall to discharge thanks to effects at the land-surface but decreases again for groundwater because of sub-surface variations.

1. Introduction

Droughts propagate in time and space. In time, droughts propagate, that is, move, through the hydrological cycle from the atmosphere to the hydrosphere. Specifically, precipitation deficits can with a time delay turn into soil moisture and streamflow deficits, which may again turn into groundwater deficits after a while (Van Loon, 2015). In space, droughts propagate from one region to another either by growing in extent or by a shift of the drought center (Herrera-Estrada et al., 2017). As droughts propagate both in time and space, their impacts increase (Stephan et al., 2021). For example, drought impacts will be more severe if a system does not just experience precipitation but also streamflow deficits as precipitation deficits can no longer be compensated by pumping water from streams for irrigation. Moreover, droughts affecting the groundwater hamper its role as a strategic water reserve (Famiglietti, 2014). Similarly, large-scale droughts are more challenging to manage than local droughts because drought management schemes relying on water transfers from one to another region may no longer be working efficiently.

Such changes in impacts are related to changes in drought properties during temporal drought propagation. Streamflow droughts often develop from precipitation droughts but occur with a time delay and are usually longer and more severe than precipitation droughts (Barker et al., 2016; Haslinger et al., 2014; Minea et al., 2022; Tijdeman et al., 2022). Similarly, groundwater droughts respond slowly to precipitation deficits and develop from prolonged periods of reduced recharge (Rust et al., 2019; Van Lanen & Peters, 2000). They typically lag further behind precipitation deficits than streamflow droughts (Li & Rodell, 2021) and the number of drought events decreases but duration increases when droughts propagate from streamflow to groundwater (Sutanto & Van

Lanen, 2020). Not all meteorological droughts develop into streamflow (Van Lanen, 2006) or groundwater droughts (Van Lanen & Peters, 2000; Wossenyeleh et al., 2021). The propagation characteristics are controlled by climate and catchment characteristics, in particular storage properties (Van Lanen, 2006; Tallaksen & van Lanen, 2004), which is why they vary by season (Li et al., 2021) and catchment (Brakkee et al., 2022; Hellwig et al., 2021; Odongo et al., 2023; Van Loon, 2015).

Most existing studies looking at the temporal propagation of drought through the hydrological cycle look at the correlation between two standardized indices, for example, the standardized precipitation index and the standardized streamflow index, at different accumulation periods, that is, time scales, to define the drought propagation time, for example, from precipitation to streamflow, as the time lag with the strongest correlation (e.g., Bloomfield and Marchant (2013); Barker et al. (2016); Hellwig et al. (2022); Odongo et al. (2023)). For example, one would be looking for the maximum correlation between the standardized precipitation index and the standardized precipitation-evapotranspiration index at different time scales if one was interested in identifying the propagation time from precipitation droughts to droughts also considering atmospheric deficits (McEvoy et al., 2012). Such a correlation-based approach neglects the variability of drought propagation times between events. To account for this variability, the propagation time should be determined at an event scale instead (Ho et al., 2021).

In addition to local characteristics, drought impacts also depend on the spatial extent of droughts, which itself depends on the strength of drought dependencies. Such dependencies describe which catchment pairs have co-experienced a certain number of drought events in the past and are also referred to as spatial connectedness. They have been investigated globally for meteorological droughts (Mondal et al., 2023) and vary strongly in space. That is, drought co-occurrence in multiple catchments during a given time of the year is likely in some regions but unlikely in other regions.

Even though drought propagation has two dimensions, temporal and spatial drought propagation are mostly studied separately. That is, temporal drought propagation within the hydrological cycle is often studied from a local, that is, catchment, perspective and spatial drought propagation is studied using one variable only, neglecting the propagation within the hydrological cycle from one variable to another. In this study, we take a holistic view on drought propagation by considering its two dimensions: the temporal and spatial one. The joint consideration of both dimensions allows us to assess how the spatial connectedness of droughts may change as droughts propagate from the atmosphere to and through the hydrosphere. We hypothesize that the connectedness of droughts increases as precipitation deficits turn into streamflow deficits thanks to synchronizing processes at the land surface, for example, widespread soil drying or lack of snowmelt, and that the connectedness again decreases as we move further to groundwater deficits because of large sub-surface heterogeneities (Haslinger et al., 2014; Hellwig et al., 2021, 2022).

Here, we test these hypotheses by assessing how spatial extent and connectedness change along the drought propagation pathway, that is, as precipitation deficits turn into streamflow and groundwater deficits. Specifically, we ask (a) how are precipitation, streamflow, and groundwater droughts spatially connected over the Alps and (b) how do spatial extent and connectedness change during drought propagation from the atmosphere to streams, and to groundwater? As the spatial propagation of drought cannot be looked at without considering the propagation of drought at a catchment scale, we also look at drought propagation from a catchment perspective and assess which fraction of meteorological and streamflow droughts propagates along the drought propagation pathway to groundwater. Using a large-sample dataset of 70 catchments in Central Europe for which precipitation, streamflow, and groundwater data are available, we are able to demonstrate that indeed drought propagation is not limited to local drought characteristics but also comprises spatial drought extent and connectedness.

2. Methods

2.1. Study Region and Datasets

Central Europe consisting of Switzerland, Austria, Southern Germany, Western France, and Northern Italy lies in the temperate climate zone and shows diverse runoff regimes ranging from rainfall-to snowmelt-dominated. In this region, we identified catchments for which both streamflow and groundwater records were available at a streamflow gauge and a groundwater well, respectively. To analyze the propagation of spatial dependencies within the hydrological cycle, we needed a spatial dataset covering the same and ideally long time period for all catchments and variables of interest (streamflow, groundwater, precipitation, and evapotranspiration). To identify such a

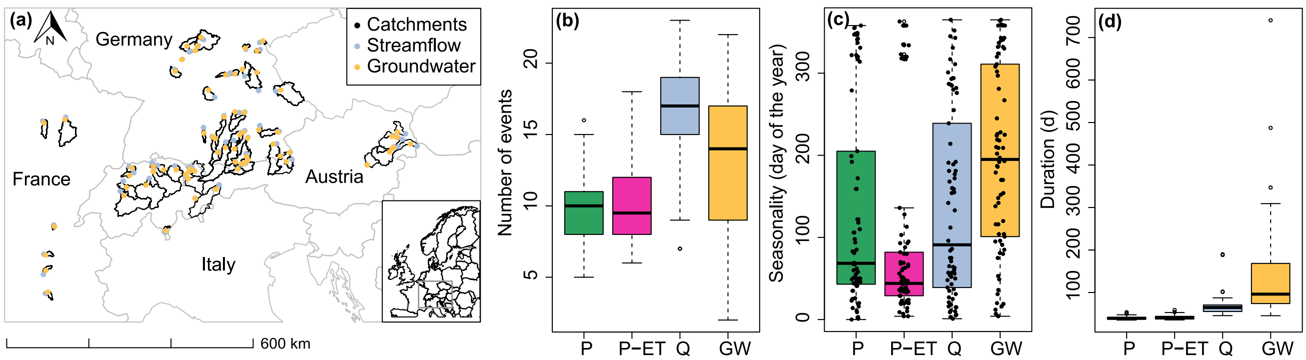

Figure 1. (a) Map of the 70 catchments in Central Europe with streamflow and groundwater data for the period 1989–2017 (b)–(d) Comparison of drought characteristics across drought types, namely, precipitation (P) drought, P-ET drought, streamflow (Q) drought, and groundwater (GW) drought: (b) number of events, (c) seasonality (day of the year computed using circular statistics and displayed using a stripchart to highlight data spread), and (d) duration. The horizontal line within the boxplot represents the median and the whiskers extend to the most extreme data point which is no more than 1.5 times the length of the box away from the box.

dataset, we assessed the trade-offs between temporal and spatial coverage and chose the period 1989–2017 as the period with the best relationship of spatial and temporal coverage as it covers 28 years of daily data for 70 catchments (Figure 1a). We chose catchments using information on data availability only without considering further metadata, for example, on the groundwater wells, as such additional constraints would have further reduced sample size. In catchments with more than one groundwater well, we chose the well most representative of the entire catchment, that is, the one closest to the streamflow gauge. The catchment selection includes catchments with areas between a lower quartile of 190 km^2 and an upper quartile of 1,150 km^2, mean elevations from 200 to 2,370 m. a.s.l., and mean annual flows between a first quartile of 835 and a third quartile of 6,980 m^3/year.

We obtained observed streamflow (Q) and groundwater (GW) time series at daily resolution from national agencies in Austria (Austrian Ministry of Agriculture, Forestry, Regions and Water Management), Switzerland (Federal Office for the Environment, FOEN), eastern France (Banque HYDRO and ADES France) and regional agencies in southern Germany (regions Baden-Württemberg (Landesanstalt für Umwelt Baden-Württemberg) and Bavaria (Bayerisches Landesamt für Umwelt)). The analysis excludes Northern Italy because streamflow records provided by the regional agencies cover a much shorter period than the one needed for the spatial dependence analysis. In addition to streamflow and groundwater data, we derived daily meteorological time series, that is, precipitation (P) and precipitation minus evapotranspiration (P-ET), for each catchment from the gridded ERA5-Land reanalysis data product (9 km resolution; Hersbach et al. (2020); ECMWF (2019)) by building the sum over all grid cells within a catchment. We relied on reanalyzes instead of observation-based data for the climatic variables because they provide both precipitation and evapotranspiration at a relatively high spatial resolution and because comparable observation-based grid products such as E-OBS do not provide evapotranspiration estimates (ECMWF, 2024).

2.2. Drought Identification

We identified drought events for each of the four variables–precipitation, P-ET, streamflow, and groundwater–using a variable threshold level approach. First, we smoothed the time series using a moving window over 30 days. Second, we computed a seasonally varying drought threshold by computing the fifteenth percentile of the variable of interest for each day of the year considering ± 15 days before the day of interest. Third, we identified negative anomalies as the daily values below this threshold. Finally, we removed events with durations shorter than 30 days to avoid the selection of minor events. This procedure was consistently and independently applied to all four variables and all 70 catchments.

2.3. Temporal Propagation of Local Droughts

We used the drought samples of the four variables to study the temporal propagation of drought characteristics locally, that is, considering each catchment individually. First, we looked at the transformation of drought characteristics (i.e., season of occurrence, number of events, and duration) from precipitation to P-ET, streamflow, and groundwater droughts. Second, we quantified the percentage of events propagating from precipitation deficits to P-ET, streamflow, and groundwater deficits, from P-ET to streamflow and groundwater deficits, and from streamflow to groundwater deficits, that is, the drought propagation rate (Sattar et al., 2019; Zhang et al., 2022). The events propagating by more than one compartment had to affect all intermediate compartments as well in order to be counted as propagating events. For example, to assess the propagation rate of precipitation to streamflow droughts, we counted the number of precipitation events first propagating to P-ET droughts and then streamflow droughts but not groundwater droughts. We allowed for a time window of 30 days for precipitation and P-ET when looking at the propagation rate of precipitation droughts and P-ET droughts, respectively, and for streamflow when computing the streamflow propagation rate. That is, we would label a precipitation drought as a drought propagating to streamflow if the streamflow drought started no later than 30 days after the end of the precipitation drought.

2.4. Temporal Propagation of Spatial Drought Characteristics

To study the propagation of spatial drought characteristics, we looked at changes in spatial drought extent and connectedness along the drought propagation pathway from precipitation to streamflow and groundwater drought. In a first step, spatial extent was computed at the annual scale and here defined as the percentage of catchments under drought for the variable and year of interest. On the one hand, we looked at the inter-annual variability of drought extent per variable. On the other hand, we assessed changes in the ratio of spatial extents of different variables, that is, the percentage of catchments experiencing a drought during any given year, to describe how spatial extents propagate from precipitation to streamflow drought or from streamflow to groundwater drought. In a second step, we quantified spatial drought connectedness using complex network analysis which enables visualizing and describing connections of large data sets (Kolaczyk & Csardi, 2020; Luke, 2015). For this, we first compiled a co-occurrence matrix quantifying for each pair of catchments how many drought events they have co-experienced in the past. Two droughts were defined as co-occurrences if they overlapped in time by at least one day. Next, we used this co-occurrence matrix to map networks of drought co-occurrences following the approach introduced by Brunner et al. (2020) for floods. Specifically, we defined catchments as being connected to each other if they co-experienced at least five drought events in the past. This information on (non-)connectedness was stored in an adjacency matrix A, which was used to build the complex network graph $G = (V, E)$, where V represents vertices, that is, network nodes (in our case catchments), and E represents edges, that is, links connecting the nodes (in our case connecting pairs of catchments co-experiencing drought events). A is defined so that

$$A_{ij} = \begin{cases} 1, & \text{if } \{i,j\} \in E \\ 0, & \text{otherwise.} \end{cases} \quad (1)$$

Using the constructed drought network, we quantified the drought connectedness of a catchment with all other catchments. Here, drought connectedness strength was defined as the node degree, that is, the number of catchments with which a certain catchment co-experienced at least five drought events in the past. Last, we computed the distance over which droughts co-occurred by computing the Euclidean distance between the outlets of any connected catchment pair. This network and connectedness analysis was performed for each of the four variables of interest (P, P-ET, Q, and GW) separately. Finally, we compared the properties (i.e., connectedness strength, and connectedness distance) of the different drought networks to describe the propagation of drought connectedness.

3. Results

3.1. Temporal Propagation of Local Droughts

The number and characteristics of droughts change as they propagate along the drought propagation pathway (Figure 1). The number of drought events lasting more than 30 days doubles when moving from the atmosphere (P and P-ET droughts) to streamflow but again slightly decreases when moving even further along the drought propagation pathway to groundwater (Figure 1a). In addition, the seasonality of droughts changes as we move further along that pathway with precipitation and P-ET droughts mainly happening in winter and spring, streamflow droughts happening a bit later in spring and into summer, and groundwater droughts occurring in

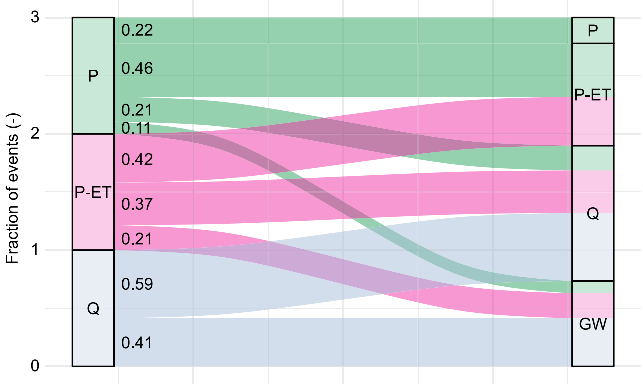

Figure 2. Fraction of events propagating from precipitation, P-ET, and streamflow droughts to droughts further along the drought propagation pathway. The bars on the left and right indicate drought origin and propagation point, respectively. Please note that the number of P, P-ET, and Q droughts has been scaled to 1, which is why we are looking at fractions.

summer and fall (see Figure 1 in Supporting Information S1 for spatial patterns in drought seasonality). Furthermore, drought duration increases from several days for precipitation and P-ET droughts to up to a few or several months for streamflow and groundwater droughts, respectively.

Different drought events show different propagation pathways: some events propagate from precipitation as far down as to groundwater while other events do not propagate at all (Figure 2). Of the precipitation droughts, ∼45% propagate further to P-ET droughts, ∼20% to streamflow droughts, ∼10% to groundwater droughts, and ∼25% do not propagate at all. Of the P-ET droughts, ∼35% propagate to streamflow droughts and ∼20% to groundwater droughts but ∼40% do not propagate at all. Of the streamflow droughts, ∼40% propagate to groundwater droughts and ∼60% do not propagate.

3.2. Temporal Propagation of Spatial Drought Characteristics

Drought propagation is not limited to the propagation of local characteristics but extends to spatial characteristics such as extent and connectedness (Figure 3 and Figure 2 in Supporting Information S1). Spatial extent is generally largest for streamflow droughts, which affect 45% of the catchments on average per year, smallest for precipitation and P-ET droughts, which both affect 25% of the catchments per year, and somewhere in between for groundwater droughts (35% of the catchments on average) (Figure 3a). However, the inter-annual variability of drought extents is large for all drought types and the ratio between drought extents of different variables varies substantially by year. While precipitation and P-ET droughts have the same spatial extent on average, some years show an increase in spatial drought extent when droughts propagate from precipitation to P-ET (e.g., year 1996) and others show a decrease (e.g., year 2006) (Figure 3b). Similarly, the spatial extent of precipitation droughts can increase (e.g., year 1994) or decrease (e.g., year 2013) as they propagate to streamflow and groundwater droughts with increases dominating across all years. In contrast, drought extent decreases during drought propagation from streamflow to groundwater in most years.

The changes in spatial extent along the drought propagation pathway are reflected in changes in the spatial connectedness patterns of precipitation, P-ET, streamflow, and groundwater droughts (Figure 2 in Supporting Information S1). Spatial connectedness increases when droughts propagate from the atmosphere (precipitation and P-ET droughts, Figures 2a and 2b in Supporting Information S1) to streamflow (Figure 2c in Supporting Information S1) but decrease again further along the propagation path when propagating to groundwater (Figure 2d in Supporting Information S1). Drought connectedness strength is quite variable across catchments for precipitation and P-ET but also for groundwater and overall strong for streamflow (Figure 4a). Connectedness distance increases along the drought propagation path with streamflow and groundwater droughts being connected over longer distances than precipitation and P-ET droughts (Figure 4b). While the strength and distance of drought connectedness changes along the drought propagation path, the spatial connectedness patterns remain similar with connectedness being strongest over Northern Switzerland and Southern Germany and weak in Austria and Southern Switzerland (Figure 2 in Supporting Information S1).

4. Discussion

We find that P-ET droughts occur as often as precipitation droughts while streamflow droughts occur twice as often, implying that deficits developing in the atmosphere are enhanced by land-surface processes (Figure 1). This is because storage processes related to snow, glaciers, soil moisture and/or groundwater can intensify certain atmospheric deficits, which are often short and do not necessarily exceed the threshold of 30 days (Jenicek et al., 2018; Van Tiel et al., 2021; Wendt et al., 2021). Our results also show that groundwater droughts occur less frequently than streamflow droughts (Figure 1), which again points to the important role of storage processes for drought development. Drought propagation from precipitation to streamflow and groundwater droughts leads to a delay in the occurrence (shift in seasonality) and an increase in drought duration. These findings corroborate findings by Liu et al. (2019), Bevacqua et al. (2021), and Sutanto and Van Lanen (2020) who for China, Brazil, and Europe also found an increase in drought duration and a delay in drought occurrence when droughts propagate from precipitation to streamflow droughts and from streamflow to groundwater droughts, respectively.

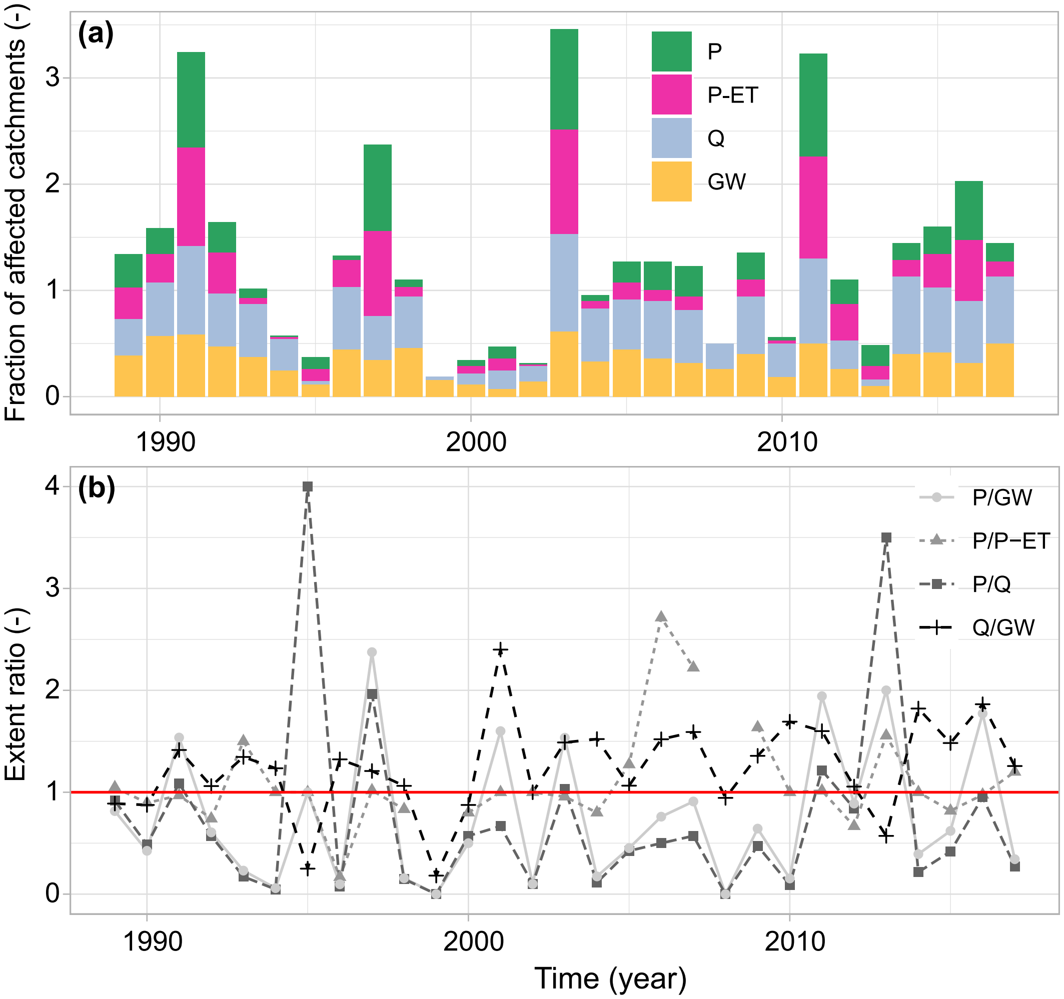

Figure 3. Propagation of spatial drought extent: (a) Spatial extent (i.e., percentage of affected catchments) per year and variable and (b) drought extent ratios for four variable pairs: P/P-ET extent, P/Q extent, P/GW extent, and Q/GW extent. (a) Each variable is normalized to 1. (b) Values larger than 1 mean that drought propagation leads to a decrease in spatial extent and values smaller than 1 mean that drought propagation leads to an increase in extent.

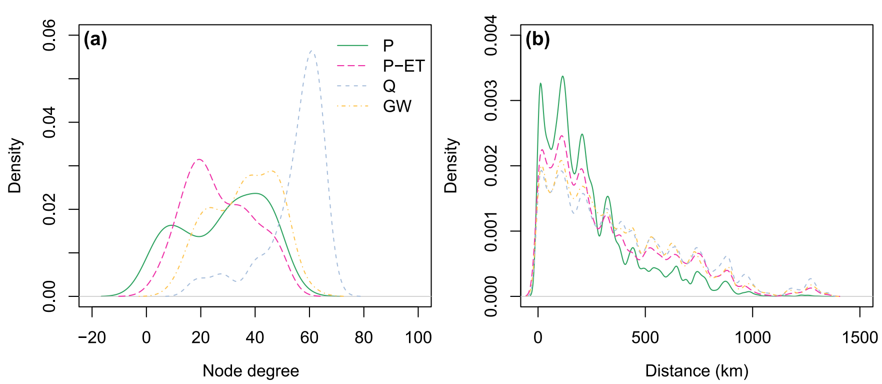

Figure 4. Drought connectedness properties for precipitation, P-ET, streamflow, and groundwater visualized as densities estimated using kernel density estimation: (a) connectedness strength (i.e., node degree distribution) and (b) connectedness distance across all catchments.

Our findings also show that two thirds of the precipitation droughts propagate to other compartments of the hydrological cycle but only 30% propagate beyond P-ET drought to streamflow (20%) or groundwater (10%) (Figure 2). In addition, we show that 40% of the streamflow droughts propagate further to groundwater droughts. Both findings again highlight the important alleviation effect of storage processes at or below the land-surface. Such drought propagation rates may vary for different climate zones as Sattar et al. (2019) found higher propagation rates from precipitation to streamflow of 30%–60% in South Korea with a humid-subtropical climate.

The close links between precipitation and P-ET droughts are confirmed when looking at spatial extents and drought connectedness, which are very similar for the two variables (Figures 3 and 4). Spatial extent and connectedness mostly increase as droughts propagate from atmospheric deficits to streamflow and groundwater (Figure 3b), which is linked to the finding that streamflow and groundwater droughts are not as short-lived as precipitation droughts and again highlights the influence of land-surface processes. For example, widespread soil moisture, snowmelt or groundwater deficits may intensify and synchronize the effects of atmospheric deficits in a similar way as a surplus of these variables leads to a spatial synchronization of flood events (Brunner & Dougherty, 2022; Brunner & Fischer, 2022). The strength of the increase varies strongly by event/year, which is likely related to the fact that each spatial event is caused by a unique set of drivers and the contribution of precipitation deficits for streamflow drought development varies widely across events (Brunner et al., 2021). The finding of an increase in drought extent during drought propagation from the atmosphere to the streamflow is in contrast to previous model- and observation-based studies for Europe and China which have shown relatively little change or even decreases in spatial drought extent as droughts propagate from precipitation to runoff (Hanel et al., 2018; Liu et al., 2019).

While drought spatial extent and connectedness increase when precipitation droughts turn into streamflow droughts, spatial extent and connectedness again decrease during the propagation of streamflow to groundwater droughts. This decrease may be related to the large heterogeneity of the sub-surface resulting in spatially variable groundwater behavior (Haslinger et al., 2014; Hellwig et al., 2017; Rust et al., 2019). Overall, the propagation of local and spatial drought characteristics are closely linked: the increase in drought duration during local drought propagation thanks to land-surface processes results in spatially more persistent hydrological than meteorological droughts. However, groundwater droughts show a weaker spatial signal than streamflow droughts because of subsurface heterogeneity.

These new insights related to the temporal propagation of local and spatial drought characteristics were possible thanks to our dataset of paired streamflow gauge and groundwater well observations complemented with climatic data from reanalyzes. While valuable and useful, our dataset also has some limitations. First, the catchments for which both streamflow and groundwater time series are available are irregularly spaced, which is unavoidable when working with observations. While such irregular spatial distribution is not optimal, it does not affect our conclusions because all variables are affected in the same way and we look at the propagation of spatial drought characteristics relative to the spatial characteristics of other variables earlier on the propagation pathway. Second, some regions are not that well represented in the dataset because available groundwater well data do not necessarily match catchments for which streamflow data are available (e.g., Baden-Württemberg, France, Austria). Improving spatial coverage would come at the cost of losing temporal coverage, which is not desirable either because studying extreme events requires sufficiently long time series to ensure a large enough sample size. Third, groundwater well data are not necessarily fully representative of the groundwater behavior at the catchment scale (Hellwig et al., 2021). Fourth, our catchment selection includes both natural and regulated catchments but regulation effects are not explicitly considered in this study even though human influences might importantly influence drought propagation (Yang et al., 2024). Last, the climate data used for the analysis were retrieved from a reanalysis data product, which may not perfectly represent observed precipitation and P-ET.

In addition to these data limitations, our results are also influenced by several methodological choices made. For example, they depend on the drought definition and several thresholds, including the percentile threshold used to identify local droughts, the connectedness threshold used to identify catchments with spatial drought connectedness, and the temporal propagation threshold of 30 days. An increase in the threshold percentile will lead to an increase in the number of events and propagation rates, while a decrease will lead to a decrease in the number of events and in propagation rates. Similarly, a decrease in the minimum drought duration threshold imposed, leads to an increase in the number of events but to hardly any changes in drought propagation rates. An increase or decrease in the connectedness threshold will lead to a decrease and increase in the number of connections,

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respectively. An increase of the propagation window will increase the propagation rate but also include events that developed from other deficits than the one under investigation. For example, increasing this time window from 30 to 60 days leads to a slight increase in the number of events propagating from precipitation to P-ET (50 instead of 46%), from P-ET to streamflow (47 instead of 37%), and from streamflow to groundwater (48 instead of 41%). While these choices will lead to changes in absolute numbers, the overall conclusions and spatial patterns remain unchanged.

The propagation of both local and spatial characteristics may change because of changes in (a) climate and (b) water management/regulation (e.g., reservoirs, water abstractions, diversions). Climate change may affect drought propagation rates locally and in space. Locally, projected increases in evapotranspiration (Dezsi et al., 2018) may lead to an increase in the likelihood of precipitation deficits propagating to streamflow and groundwater because of intensified soil drying. Projections for Irish catchments show that this is indeed the case when looking at the end of the century (Meresa et al., 2023). Similarly, the probability of meteorological droughts propagating to hydrological events, shows modest increases under the climate change projections considered. In addition, the increasing importance of snow deficits for drought development (Brunner et al., 2023) may lead to reduced groundwater recharge (Xanke & Liesch, 2022) which might favor the development of groundwater drought and therefore increase propagation rates from streamflow to groundwater droughts. However, projections for the UK point into the opposite direction and show that the proportion of streamflow droughts propagating to groundwater droughts will decrease (Tanguy et al., 2023). Furthermore, increases in precipitation variability (Wood, 2023) may lead to increases in inter-annual and inter-event variability of propagation rates.

Climate impacts on drought propagation are likely not limited to local drought propagation but extend to spatial propagation because of spatially simultaneous changes in land-surface properties including decreasing soil moisture and snowmelt contributions. Increases in spatial precipitation and streamflow drought extents are already visible in Europe (Hanel et al., 2018) and may lead to an increase in the spatial connectedness of streamflow and groundwater droughts - further increasing the differences between precipitation and hydrological drought connectedness. Projections for the United Kingdom support this hypothesis by showing that the spatial dependence of summer streamflow droughts increases by the end of this century (Tanguy et al., 2023). Assessing impacts of future changes in temporal drought propagation requires the use of a climate-hydrological model chain. However, Van Loon et al. (2012) found that drought propagation features were poorly reproduced by large-scale models because runoff reacted immediately to precipitation.

In addition, changes in water management may both reduce or intensify drought propagation. Water storage in reservoirs during precipitation droughts might increase the likelihood of drought propagation, while water releases may decrease drought propagation likelihood. Influences of reservoir regulation on the temporal propagation of local drought characteristics have been detected in China (Xing et al., 2021; Yang et al., 2024), the United States (Tijdeman et al., 2018), and at a global scale (Fuentes et al., 2022). Brunner (2021) have shown that the effect of reservoirs on droughts is not limited to local characteristics and extends to spatial dependencies. Specifically, they found that in the United States, reservoir regulation leads to an increase in drought connectedness in summer but to a decrease in connectedness in winter. These findings suggest that reservoirs have the potential to change how spatial precipitation drought connectedness propagates to streamflow drought connectedness. Similarly, spatially simultaneous water abstractions from groundwater may increase the spatial connectedness of groundwater droughts.

Our findings have implications for drought prediction and management. Since 30% of the atmospheric droughts propagate further along the drought propagation pathway and 40% of the streamflow droughts turn into groundwater droughts, local and spatial streamflow and groundwater droughts are to some degree predictable by monitoring droughts happening earlier along the propagation pathway. However, the full extent of hydrological drought cannot be predicted using information on atmospheric variables (precipitation, P-ET) and requires information on land-surface dynamics. The finding that streamflow droughts are more widespread and spatially connected than groundwater droughts suggests that groundwater abstractions still have some potential to alleviate widespread streamflow droughts.

5. Conclusions

Our results show that both local and spatial drought characteristics propagate in Alpine catchments. Droughts are delayed and prolonged as deficits propagate along the drought propagation pathway from the atmosphere to rivers and groundwater. However, only a fraction of precipitation deficits propagates further along the drought propagation pathway. While 75% of the precipitation droughts still propagate to P-ET droughts, only every third precipitation drought turns into a streamflow drought. However, those droughts that have propagated to streamflow have a 40% chance to further propagate to groundwater. In addition, drought extent increases and connectedness intensifies during drought propagation from precipitation to streamflow thanks to synchronizing effects of the land-surface but decreases again for groundwater because of sub-surface heterogeneity. While the strength of connectedness changes during drought propagation, spatial connectedness patterns are similar for all variables. Drought propagation properties may change with water management and climate because of changes in atmospheric, land-surface, and storage processes. The finding that both local and spatial drought characteristics propagate suggests that both local and regional hydrological droughts can be predicted only to a certain degree by monitoring precipitation and evapotranspiration.

Data Availability Statement

The data supporting this research is available through HydroShare (Chartier-Rescan & Brunner, 2024).

Acknowledgments
The authors acknowledge funding from the Swiss National Science Foundation (SNSF) through project PZ00P2_201818.

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