Anthropogenic activities alter drought termination

By *J Margariti, S Rangecroft, S Parry, D E Wendt & A F Van Loon*

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Abstract

Despite the increasing influence of human activities on water resources in our current Anthropocene era, the impacts of these activities on the duration, rate and timing of the recovery of drought events, known as the drought termination phase, remain unknown. Here, we present the first assessment of how different human activities (i.e. water abstractions, reservoirs, water transfers) affect drought termination. Six case studies in Europe were used to analyse the human influence on streamflow drought termination characteristics. For all case studies, we compared a human-influenced time-series of streamflow (observation data) and a naturalised time-series (modelled data) for the same period. Overall, results clearly demonstrate the influence of human activities on drought terminations in all the studied catchments. Groundwater abstractions, reservoirs and mixed influences were all found to increase the average duration of drought termination, whereas water transfers into the catchment decreased drought termination duration. Results also show that average drought termination rates increased in all case studies due to the human influence. Furthermore, start and end months of the termination phase were more skewed to certain months in human-influenced data than in the naturalised situation. Future research could extend this new knowledge by looking to add further case studies and covering different human activities to gain a wider understanding on how human actions modify hydrological droughts and their recovery. Furthering this work could also help to improve the forecasting of drought recovery in the Anthropocene, which is important for informing drought management decisions.

1. Introduction

Many regions of the world will likely see an increase in drought occurrence and severity in the 21st century (Dai, 2011; Kirono *et al*., 2011; Stahl *et al*., 2012), yet there are numerous areas in which our understanding of drought processes is far from complete. This hinders our ability to forecast, manage and respond to water deficit anomalies, especially in relation to anthropogenic activities and feedbacks within drought (Van Loon *et al*., 2016a). Arguably, a critical yet neglected phase of drought is the re-wetting stage, termed drought termination (Parry *et al*., 2016a). Drought termination is a characteristic of a drought event that describes its ending. It is not only a point in time denoting when a drought is said to have ended, but a quantifiable event with a temporal profile (see Figure 3 in Parry *et al.* 2016a). An understanding of why, when and how a drought is likely to terminate is valuable information for water managers. Such knowledge is crucial for deciding how the transition from depleted to replenished water supplies is operationally handled (Hannaford *et al*., 2011; Bell *et al*., 2013). Heim and Brewer (2012) stress the importance of including drought termination within any monitoring framework. As drought terminations are often disruptive, abrupt events (Dettinger, 2013), their study is also merited to help predict associated impacts of high flows and implications for water quality (Loecke *et al*., 2017). Yet the propagation, drivers, physical processes and feedbacks of drought termination through the hydrological cycle are currently poorly understood (Parry *et al*., 2016a).

One of the earliest studies on the topic used the Palmer Drought Severity Index (PDSI; Palmer, 1965) to calculate the amount of rainfall required for drought termination over different timeframes (Karl *et al*., 1987). Since then, the question of the amount of rainfall required to terminate a drought has been explored using models or climate ensembles of rainfall forecasts to calculate the likelihood of termination under given meteorological inputs (Bell *et al*., 2013; Pan *et al*., 2013; Antofie *et al*., 2014; Parry *et al*., 2018). Whilst such studies are important, this area of research is still in its infancy. Research to-date often considers events in soil moisture or subsurface stores, whereas there is a need to address hydrological drought termination more holistically.

In addition to the natural drivers of drought termination (i.e. climate, catchment type, geology, etc.), there are numerous ways in which humans modify land-use, water partitioning and hydrological regimes, which is especially crucial for the termination of hydrological drought compared to meteorological and soil moisture drought. Human-induced changes are known to have a significant effect on the hydrological cycle (Barnett *et al*., 2008) and are expected to increase due to a growing population (Alcamo *et al*., 2003). Understanding the processes impacted by human activities, such as those in the drought termination phase, is fundamental for the effectiveness of drought forecasting, monitoring and early warning systems. This information is subsequently invaluable for the formulation of adaptive responses to drought conditions and managing water scarcity, especially given that it is often human-influenced systems that we are most reliant upon for our water supply (Barker *et al*., 2016).

Despite the increasing influence of human activities on water resources in our current Anthropocene era (Steffen *et al*., 2015; Hamilton, 2016), the impacts of these activities on drought termination remain unknown and unexplored. For the first time here we assess the impact of human activities on changes in drought termination characteristics within different catchments by comparing human-influenced (observed) data with naturalised (modelled) data. The study aim is to assess if and how human modifications affect the drought termination phase by considering the human activities of reservoirs, abstraction, urbanisation and water transfer. We use a framework that can be applied to other human activities, catchments, climates etc.

It is expected that human influences will have a detectable effect on drought termination metrics, as they are known to do on other drought characteristics, thanks to the resulting modification of water availability and hydrological regimes (Van Loon and Van Lanen, 2013; 2015; Wada *et al*., 2013; Tijdeman *et al*., 2018). The type of response seen in the termination phase is predicted to be reliant on the type of human activity dominant in the catchment.

2. Methods

In this section, we describe the methods used for this analysis. We introduce the case studies from across Europe, the data, the drought analysis and drought termination characteristics, and the comparisons to calculate the human influence. This work focuses on streamflow drought, defined as a sustained period of below 'normal' water availability in river discharge (Mishra and Singh, 2010). We focus on streamflow droughts influenced by human activities (human-modified droughts, Van Loon *et al*. (2016a)).

2.1 Case studies and data

Six case studies in Europe were used to analyse the human influence on streamflow drought termination characteristics (Figure 1; Table 1; Appendix 1). These case studies were chosen based on the availability of an observed and a naturalised streamflow time-series for the same discharge gauge within the catchment. The datasets used have no missing data. All case studies compared the human-influenced time-series of streamflow (observation data) and the naturalised time-series (representing the 'natural' situation) for the same period. Compared to an approach in which post-disturbance time series are compared with pre-disturbance time series, a benefit of using naturalised data is that the same time period and input data (i.e. precipitation) are used for both the human and natural situations. Any differences seen in streamflow therefore should be due to human activity, given uncertainties in both observations and model data.

Table 1. Summaries of case study details, their direct anthropogenic influences and naturalisation methods.

Country	Basin	Area (km^2)	Human Activity	Climate Class[1]	Source	Dataset period	Naturalisation Method
Czech Republic	Svitata	419	Groundwater abstraction for drinking water/public water supply (PWS)	Dfb	Van Loon and Van Lanen (2015)	1975 – 1990	BILAN lumped conceptual rainfall-runoff model, calibrated on a pre-disturbed period
Czech Republic	Bilina	1,071	Water transport to catchment from nearby basin	Cfb	Van Loon and Van Lanen (2015)	1961 – 1990	BILAN lumped conceptual rainfall-runoff model, calibrated on a pre-disturbed period
France	Ariège	1,340	Hydropower dam/reservoir, water transfer[2]	Cfb	Banque Hydro French database (2017)	1990 – 2004	Naturalisation via reconstruction
Spain	Upper-Guadiana	16,480	Groundwater abstraction for irrigation and artificial drainage	Csa, Csb, Bsk	Van Loon and Van Lanen (2013)	1980 – 2001	HBV hydrological model, calibrated on a pre-disturbed period
United Kingdom	Thames	9,948	Mixed influence (reservoirs, abstraction for PWS, industry and agriculture, effluent returns[1] and urbanisation)	Cfb	NRFA (CEH, 2019)	1900 – 2017	Naturalisation by decomposition
United Kingdom	Lee	1,036	Mixed influence (reservoirs, abstraction for PWS, industry and agriculture, effluent returns[1] and urbanisation)	Cfb	NRFA (CEH, 2019)	1903 – 2016	Naturalisation by decomposition

[1] Köppen climate classification used (Kotek *et al*., 2006).
[2] Denotes the lesser of the two (or more) human influences where they are not significant in terms of dominance in the catchment.

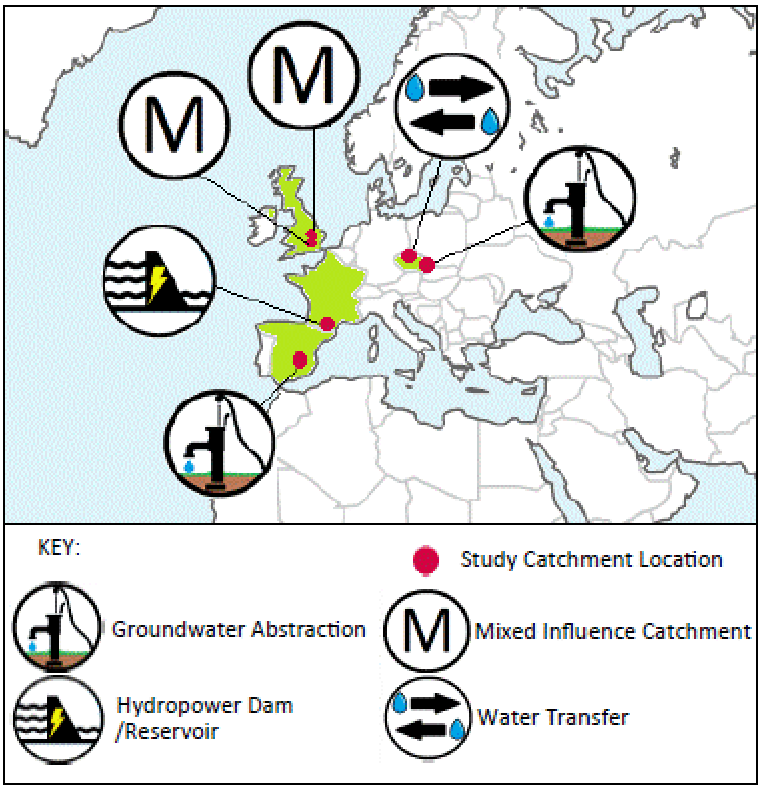

Figure 1: Study catchments. Location of the six study catchments across Europe and the dominant human activity for each.

Data was naturalised prior to acquisition using the naturalisation technique most suitable for each case study (see Appendix 1). Monthly data was used, therefore where required, specific discharge values were converted from a daily to a monthly time-step by calculating monthly sum values. Although data lose finer details at this resolution, using a monthly time-step has the advantage of negating the need for pooling, as minor droughts (<1 month) are removed (Fleig *et al*., 2006).

2.2 Identifying drought events

The method chosen to define drought conditions is important as it can influence the results obtained (Fleig *et al*., 2006; Heudorfer and Stahl, 2016). Here, the threshold level method was used to identify drought events (Yevjevich, 1967; Hisdal *et al*., 2004). The threshold level method identifies drought periods as periods when discharge is below a predefined threshold, calculated using the average of multiple years of streamflow data at a certain percentile of the flow duration curve (Van Loon, 2015). We used the 80th percentile (Q_{80}), frequently used for identifying drought (Hisdal and Tallaksen, 2000; Fleig *et al*., 2006). As all catchments used here have flow regime seasonality, the variable threshold level method was deemed most appropriate for use (Fleig *et al*., 2006) rather than a fixed threshold. The Q_{80} threshold for each catchment was calculated using the full length of the natural dataset, which was then used to identify drought events in both the natural and human-influenced data. This was important to effectively show the impact of human activity on hydrological droughts

(Liu *et al*. 2016; Rangecroft *et al*., 2019) and their termination characteristics. Ideally, a time period of at least 30 years of data is used to establish the drought threshold (McKee *et al*., 1993). As it is often difficult to obtain appropriate datasets of this length, time-series used here varied from 14 to 117 years in length, depending on the case study.

Drought event analysis produced several drought characteristics (frequency, timing, duration, deficit volume, drought maximum intensity) (Table 2, Figure 2). We subsequently calculated drought termination characteristics.

Table 2. Summaries of drought and drought termination metrics used in this study and their calculations.

Drought Characteristic	**Description**
	Drought Events
Frequency (DF)	Number of droughts identified in time-series.
Timing	Date of drought onset and drought termination for each event.
Duration (DD)	Number of months spent in drought for each event.
Deficit (D_{def})	Water volume (mm) below Q_{80} lacking for each event.
Drought Maximum Intensity (MI)	Most intense point for each drought event. Calculated as follows: $$Drought\ Maximum\ Intensity = Max(Q(t) - Threshold(i))\ if\ Q(t) < Threshold(i)$$ *Q* is the flow value for month *t*, *Threshold* is Q_{80} for the same month in the year and *i* is the timestep. The MI using the (variable) threshold level method is therefore the largest distance between Q and the Q_{80} during an event.
	Drought Termination
Drought Termination Start (DT_{start})	The first month of the drought termination phase (DT_{start}) is the month where the maximum intensity (MI) is reached. DT_{start} is calculated for each event.
Drought Termination End (DT_{end})	The last month of the drought termination phase (DT_{end}) is the last month of the drought event (i.e. the last month when discharge < Q_{80} drought threshold). DT_{end} is calculated for each event.
Drought Termination Duration (DTD)	Number of months encompassed between DT_{start} and DT_{end} (inclusive) for each event.
Drought Termination Rate (DTR)	Drought minimum divided by drought termination duration (mm/month) for each event.

2.3 Drought termination

Drought termination can be characterised by its duration, rate of recovery, and seasonality (Nkemdirim and Weber, 1999; Mo, 2011; Parry *et al*., 2016a). Our definitions for the drought termination phase for each drought event are described in Table 2. Figure 2 shows a conceptual diagram of how the termination phase was defined and the metrics calculated for each drought event. Drought events were divided at the drought maximum intensity (MI) (Bravar and Kavvas, 1991). The first month of the drought termination phase (DT_{start}) is therefore the month where the MI is reached (Figure 2). The last month of drought termination phase (DT_{end}) is the last month of the drought event, defined when discharge exceeds the Q_{80} drought threshold. A drought event and its termination phase therefore end at the same point in time. The drought termination duration (DTD) is the number of months encompassed between DT_{start} and DT_{end} (inclusive). The drought termination rate (DTR) is the rate at which the system changes from being in a state of most intense drought state to non-drought conditions.

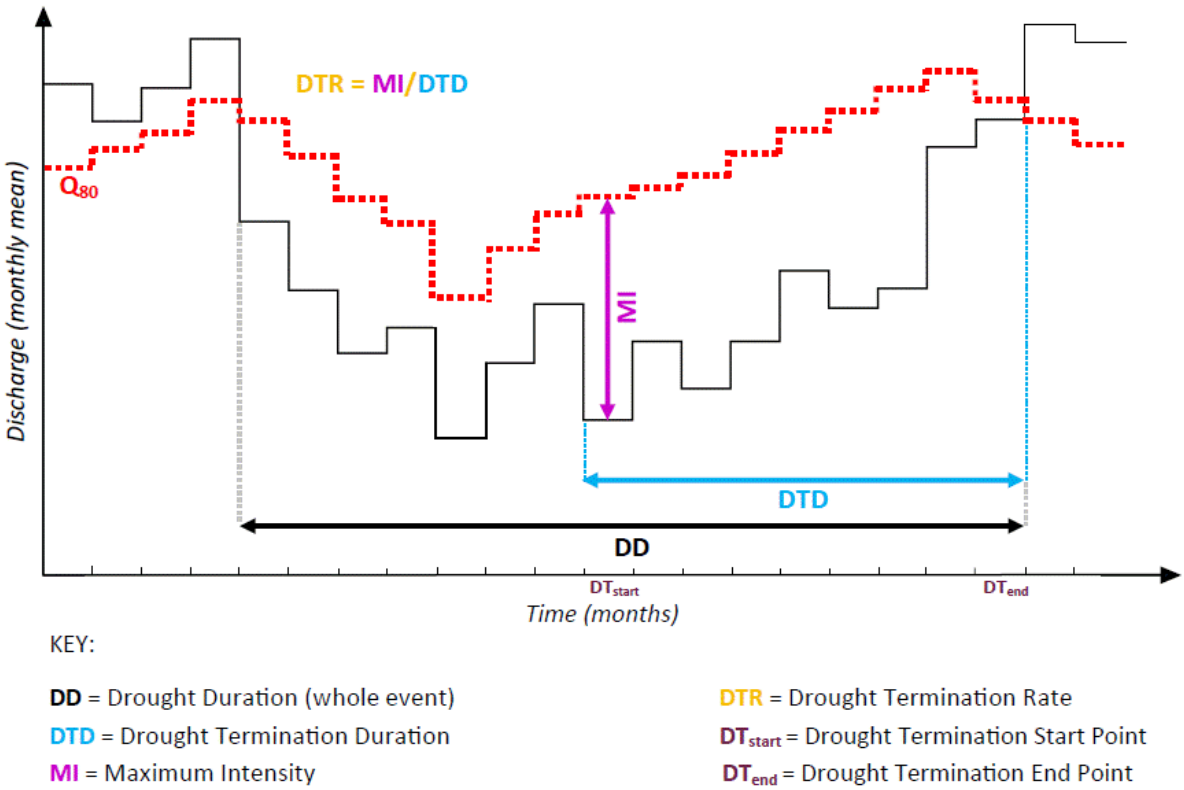

Figure 2: Definition of drought termination. Conceptual diagram of drought termination characteristics and definitions used.

2.4 Quantifying the human influence

2.4.1 Human influence on drought termination duration and rate

Drought termination characteristics per events were averaged over all events in the time period for each case study. Although it would be interesting to look at individual events, droughts identified in human-influenced and naturalised time-series could not be matched and compared like-for-like, therefore comparisons were achieved based on averages. Results were compared between the drought characteristic of the naturalised data (X_{nat}) and the drought characteristic of the human-influenced data

(X_{hum}) to quantify the size and direction of change in drought termination characteristics using Equation 1. Percentages reported are the change in the human-influenced conditions relative to the naturalised situation.

$$\% \text{ change due to human influence} = [(X_{hum} - X_{nat})]/X_{nat} * 100 \qquad \text{(Equation 1)}$$

2.4.2 Human influence on timing of drought termination

Differences in the timing of termination in human-influenced and naturalised data were presented visually. Histograms showing the frequency of termination start and end month were compared for both datasets for each catchment. To ensure valid comparison, as the number of drought events were not equal in human and natural data, the number of drought terminations starting/ending in each month were converted to a percentage of the total number of drought events.

3. Results

3.1 Human influence on drought events

The influence of human activities is evident in all catchments when visually comparing the two time-series plots for each catchment (Figure 3). With the exception of the Bilina case study (Figure 3b), droughts events are more severe, frequently last longer and have greater deficit volumes in human-influenced data. The human-influenced time-series for the Bilina catchment shows the mitigation of drought compared to the naturalised time-series.

The overall direction of change in drought characteristics due to anthropogenic activities is negative (drought characteristics are aggravated, Table 3). On average, drought duration is up to 471% longer and maximum intensity is up to 1084% greater in human-influenced data compared to naturalised data. Average drought deficit volumes in human-influenced data also exceed those of naturalised data by over 100% in four out of the six study catchments (reaching up to 7149% higher). Only the Bilina case study displays evidence of drought amelioration. Statistics in Table 3 reveal that larger increases were observed in the average maximum intensity and deficits of drought events in human-influenced data than in drought duration.

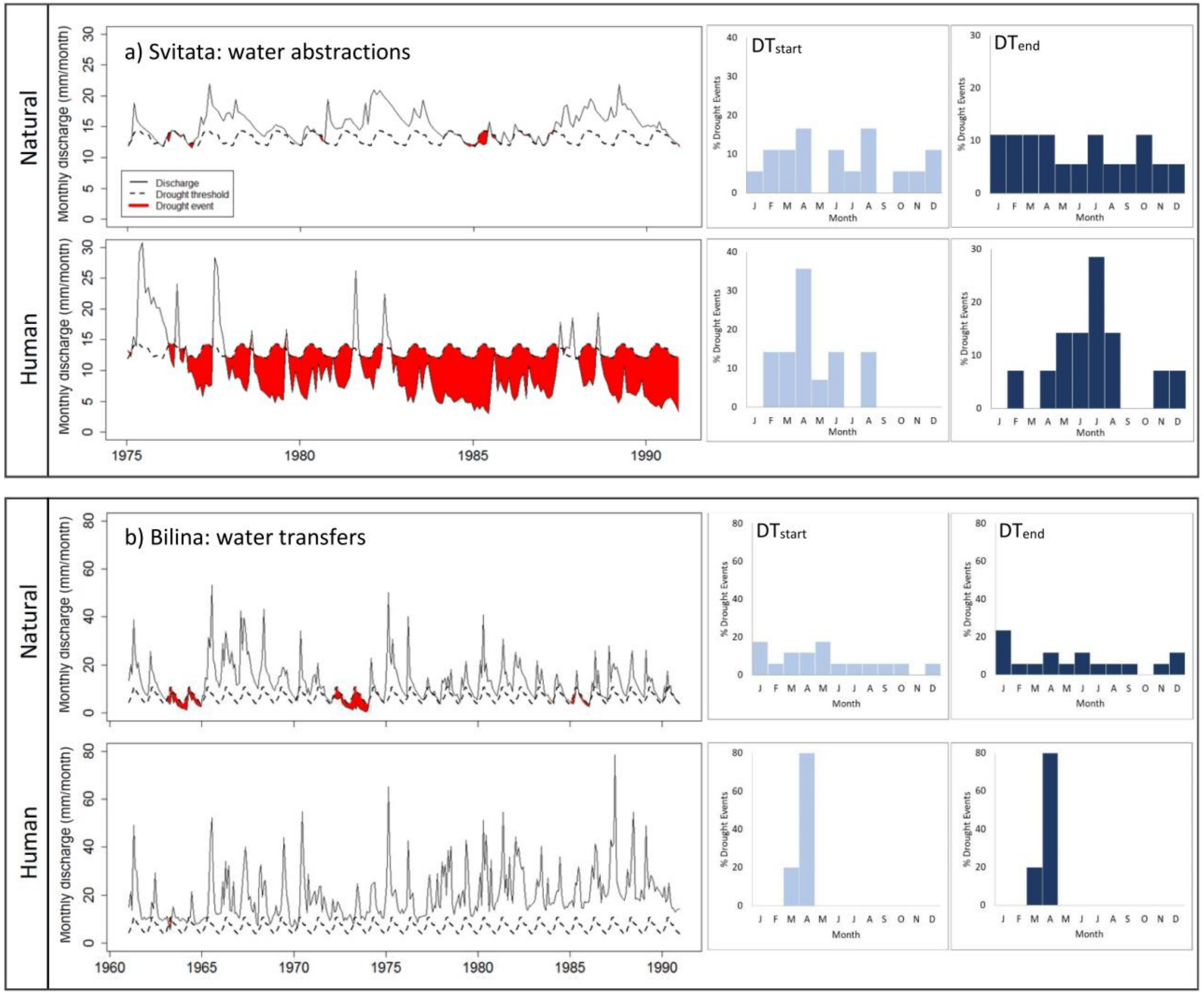

Figure 3: Human-influenced and natural droughts and the timing of drought termination. Time-series and drought events identified (red areas) for a) Svitata and b) Bilina case studies. Relating histograms display the frequency (as % of drought events) of termination start (light blue) and end months (dark blue) for naturalised (top) and human-influenced (bottom) drought events.

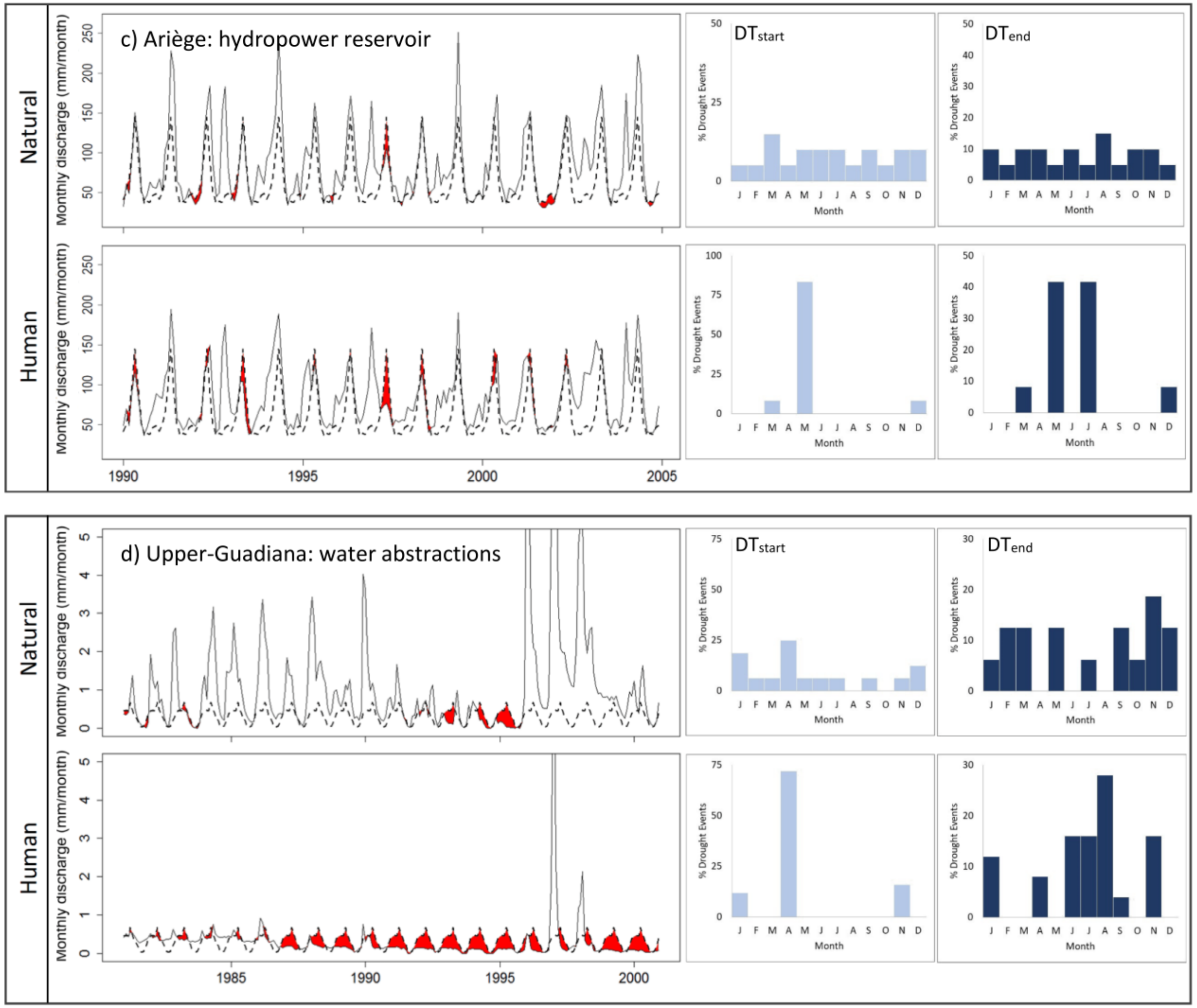

Figure 3 (continued): Human-influenced and natural droughts and the timing of drought termination. Time-series and drought events identified (red areas) for c) Ariège and b) Upper-Guadiana case studies. Relating histograms display the frequency (as % of drought events) of termination start (light blue) and end months (dark blue) for naturalised (top) and human-influenced (bottom) drought events.

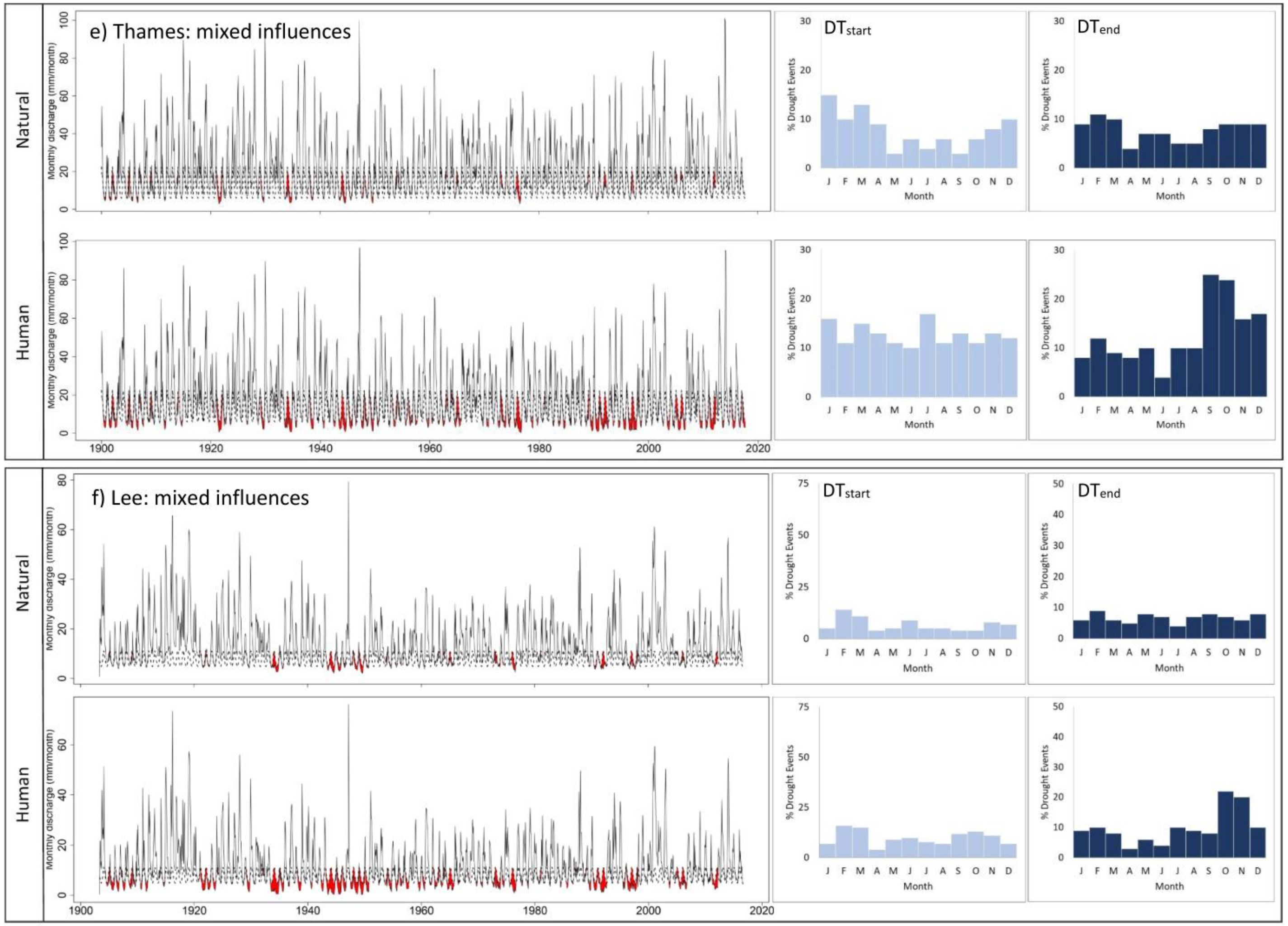

Figure 3 (continued): Human-influenced and natural droughts and the timing of drought termination. Time-series and drought events identified (red areas) for e) Thames and f) Lee case studies. Relating histograms display the frequency (as % of drought events) of termination start (light blue) and end months (dark blue) for naturalised (top) and human-influenced (bottom) drought events.

Table 3. Percentage change results from naturalised to human-influenced data for drought and drought termination metrics. Any percentage change of 100% or above is in bold to highlight the high magnitude of change.

Case study	Dominant human activity	Drought metrics: % change due to human influence				Drought termination metrics: % change due to human influence	
		Drought frequency (DF)	Mean drought duration (DD)	Mean drought deficit (D_{def})	Mean maximum intensity (MI)	Mean termination duration (DTD)	Mean termination rate (DTR)
Svitata, Czech Republic	Abstraction	-22	**+471**	**+7149**	**+1084**	**+275**	**+332**
Bilina, Czech Republic	Water transfer	-71	-72	-85	-8	-65	**+115**
Ariège, France	Hydropower dam	-40	+25	**+194**	**+188**	+36	**+130**
Upper-Guadiana, Spain	Abstraction	+56	+95	**+204**	+83	+16	+38
Thames, UK	Dam, abstraction, urbanisation	+65	+36	+83	+24	+26	+4
Lee, UK	Dam, abstraction, urbanisation	+47	+41	**+128**	+60	+12	+62

3.2 Human influence on drought termination

Overall, the influence of human activities on drought terminations is present in all catchments (Table 3). There is an increase in drought termination duration in all case studies except Bilina and higher termination rates in all case studies due to the influence of human impacts.

Human influences alter drought termination duration compared to the naturalised situation. Drought aggravating anthropogenic activities (i.e. water abstractions, mixed influences, hydropower reservoir; Figure 3a and 3c-f) all increase the mean duration of drought termination (Table 3). This means that on average, these human-influenced systems take longer to transition from the point of a drought's maximum intensity to reaching non-drought conditions. Variability was observed across all case studies in the magnitude of change, likely due to the differences in the dominant human activity. The increase in termination duration was remarkably pronounced in the Svitata case study, a catchment impacted by abstraction. The human activity of water transfers into the catchment that alleviated droughts themselves (Figure 3b, Bilina case study) also decreased drought termination duration (Table 3).

Average drought termination rates increase in all case studies due to the human activities, meaning the rate at which the system recovers from drought is faster in human-influenced systems (Table 3). This means that on average, human activities increase the rate at which a system changes from its most intense month of drought to non-drought conditions. This finding is true for all human activities, although the magnitude of change is larger in the Svitata, Bilina and Ariége catchments.

Since termination rate is calculated from maximum intensity (MI) and termination duration (DTD, see Figure 2), the change is termination rate is the result of changes in these two variables. For case studies with drought-aggravating human influences (all except Bilina), the increase in drought termination rate is caused by the increase in MI in the human-influenced situation, despite the smaller increase in DTD. For the Bilina case study, however, the human activity decreased MI, but DTD decreased more, also resulting in an increased termination rate. This is discussed further in Section 4.

The influence of human activities is seen in the timing of drought termination. Termination start and end months in human-influenced catchments are often concentrated in a smaller number of months and/or in one season (Figure 3). Peaks in most frequent months for the start and end of termination are amplified in human-influenced droughts. For example, in the Upper-Guadiana, August was the most frequent month for termination beginning in 25% of events in the natural data, whereas in the human data over 70% of terminations began in April (Figure 3a). Results from the two UK catchments possibly indicate that human activities make drought termination more likely to start towards the end of the dry season (summer) and end at the beginning of the wet season (winter).

4. Discussion

4.1 Drought termination duration

An increase in drought termination duration was observed in nearly all case studies due to the influence of human activities. Human activities that aggravate drought, such as water abstraction, manifested in longer drought termination in all affected catchments as a result of a decrease in water availability compared to the natural situation. Water abstractions influence streamflow drought and the severity of the influence is related to the amount of abstraction (Tijdeman *et al*., 2018). Similarly, reservoirs have also been found to aggravate streamflow drought downstream (Firoz *et al*., 2018; Tijdeman *et al*., 2018). This likely explains the results obtained here for drought termination duration, as the decrease in water availability compared to the natural situation means longer is required for the system to recharge and return to non-drought levels. The Bilina catchment was an exception to the results with a decrease in drought termination duration observed as a result of water transfers into the catchment. In this catchment, the low flows are artificially increased (Rolls, *et al*., 2012). As this activity ameliorates drought conditions (Soulsby *et al*., 1999; Xu *et al*., 2016), shorter, less intense human-influenced droughts take less time to return to non-drought conditions compared to the naturalised situation without water augmentation.

It is therefore deduced that drought termination duration is related to the change in drought duration and severity (i.e. maximum intensity and deficit) as a result of human activities, the scatterplots of which are shown in Figure 4. However, due to the small sample size we cannot determine a valid relationship. More data would be needed to test the validity of the suggested correlation between the drought and drought termination metrics.

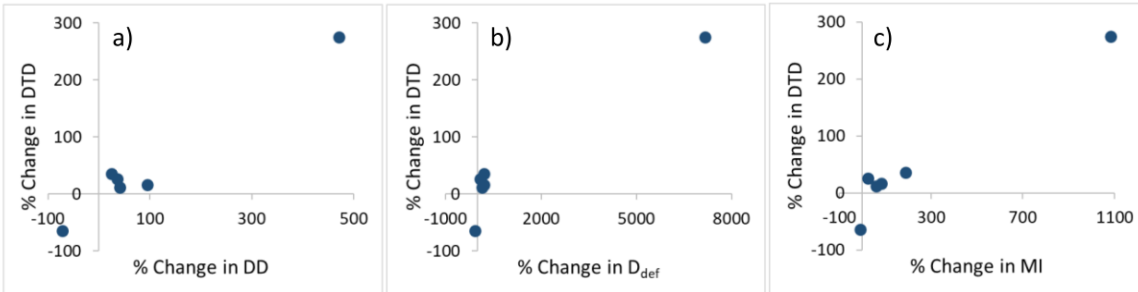

Figure 4: Correlation between drought termination duration and drought metrics. Relation between the % changes in a) drought termination duration and drought duration; b) drought termination duration and drought deficit; and c) drought termination duration and maximum intensity.

4.2 Drought termination rate

Anthropogenic activities increase the average rate at which a system changes from drought at its maximum intensity to non-drought conditions in all case studies. The most likely explanation for this is that the drought maximum intensity that begins the drought termination phase is typically lower in human-influenced situations (Figure 3, Table 3), resulting in larger drought termination rate values.

We would have expected that, compared to the naturalised scenario, drought termination rate would be slower in case studies where drought is aggravated if water is being removed from the system for human use. If human-influenced droughts are more intense than natural droughts, the magnitude of change in streamflow required between the maximum intensity and non-drought conditions is greater. It appears that the impact of the range of human activities examined here have the effect of making this transition from drought at its worst back to 'normal' conditions happen quicker, despite the intensities and deficits observed being much larger. This could be due to active management during times of drought (Scanlon *et al*., 2016), a change in hydrological pathways (i.e. more surface runoff), or a change in water demand over different times of year, allowing the system to recover when pressure on the hydrological system is low (i.e. wet season) (Ho *et al*., 2016). The natural processes driving drought termination may also be consistently great enough to compensate for a higher drought maximum intensity due to human activities.

The scatterplots of drought and drought termination rate metrics (Figure 5) show a possible relationship, but again more data is required to test validity.

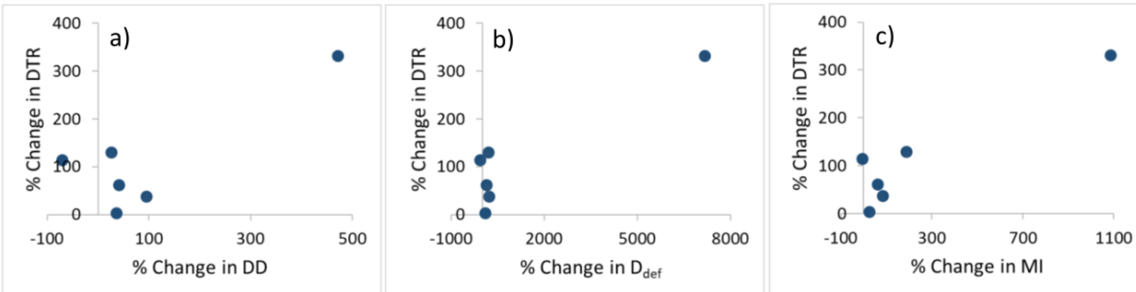

Figure 5: Correlation between drought termination rate and drought metrics. Correlations between the % changes in a) drought termination duration and drought duration; b) drought termination duration and drought deficit; and c) drought termination duration and maximum intensity.

Importantly, it is worth examining the question of what denotes a desirable drought termination rate. Whether a faster rate is a 'desirable' effect of human influences will likely depend on the circumstances of individual events or the intended group of interest (i.e. an ecosystem, specific biota or a human focus). The nature of the system in drought and whether the drivers behind the termination phase cause any further issues (i.e. intense rainfall leading to flooding) are factors that would contribute to a (possibly contradictory) definition of a desirable termination rate. For instance, although water managers who are eager to lift water restrictions might favour a quicker drought termination rate, a rapid rate caused by high precipitation events following dry spells can compromise water quality (via high levels of accumulated sediment and/or pollutants in runoff) and its suitability for drinking water (Parry *et al*., 2016a). Further work is recommended to refine suppositions on this topic.

4.3 Timing of termination

Human influences studied here create stronger seasonal patterns of when drought termination is most likely to occur. Patterns in the timing of termination were found to either become amplified or shift depending on the human activity the catchment was subjected to. The timing of termination start and end months for human-influenced droughts in the Ariège and Bilina basins alter greatly compared to the naturalised situation. This is attributed to the artificial flow regime created by the reservoirs and water transfers (Firoz *et al*., 2018). Changes are highly pronounced in the Ariège catchment, however it is likely that the utility of the reservoir (hydropower vs irrigation or drinking water supply) is an important factor in the resulting flow regime and consequent timings of downstream drought events (Rangecroft *et al*., 2019). Catchments influenced by abstractions tend to have naturally-existing patterns in their timing of termination amplified, seen especially in the Svitata and somewhat in the Upper-Guadiana, Thames and Lee, possibly relating to increasing drought occurrences during low-flow periods.

It has previously been stated that drought termination depends on the probability of a given region to receive large positive precipitation anomalies needed to end drought (Karl *et al*., 1987; Antofie *et al*., 2015). Mo (2011) established that [meteorological and agricultural] drought is more likely to end at the beginning of the wet season. In addition to precipitation anomalies, human activities are known to play a key part in moderating the seasonal cycle of water availability. For example, a demand for water for irrigation or potable supply that differs between summer (growing season in Europe) and winter often determines seasonal abstraction regimes (Wada *et al*., 2013). It is possible that as a result the seasonal cycle of a catchment is enhanced, causing more synchronicity in drought termination start and end months (i.e. due to the most water use during the low flow period).

4.4 Limitations and uncertainties

Any study using a hydrological model will have associated uncertainties (Beven, 1993; Gupta *et al*., 1998; Walker *et al*., 2003). This is an important consideration as uncertainty determines model confidence in simulating the naturalised situation, which was the basis of the comparisons in this work. Where results are published, levels of uncertainty are within acceptable limits and model performance is good (Van Loon and Van Lanen, 2013; 2015). However, re-wetting and recovery are not always simulated well in hydrological models (Birkel *et al*., 2011) and therefore the processes most relevant to drought termination (i.e. soil moisture or subsurface stores) may have larger uncertainties. When naturalisation uses information on abstraction licence limits, this assumes that water users are using the full allowance of their licence. Potential inaccuracies are introduced if full licence limits are not being utilised, however information on actual abstracted volumes is often sensitive and thereby very difficult to obtain.

Variation exists between the method used to arrive at the naturalised time-series for some case studies (Appendix 1). Different methods of naturalisation introduce some uncertainty into cross-catchment comparisons due to the lack of uniformity in the processes considered and calculations used to produce the naturalised flow record. We expect that this could influence the magnitude of change, but not the direction of change, therefore our conclusions would remain unaffected.

The brevity of available hydrological records is a constraint for most studies of drought (Barker *et al*., 2016). A small sample size due to the limited number of appropriate catchments with an available human-influenced (observed) and naturalised time-series, and also in terms of the total number of drought events identified (i.e. the Bilina case study had only five drought events in the human-influenced time-series), could limit results. This could be addressed by expanding the number of case studies in future research.

Hydrometric accuracy (particularly at low flows) and the evolution of or updates to a gauge station over time means it is often impossible to have an accurate, homogeneous flow record. This creates uncertainty, particularly affecting stations with longer records such as those of the Thames (Marsh and Harvey, 2012) and the Lee. However, it was recognised that the benefit of using these longer records in analysis outweighs the disadvantages of uncertain hydrometric accuracy.

Where more than one predominant human activity is taking place (i.e. Thames and Lee), it is acknowledged that the overall 'net' effect of activities is observed, making it difficult to separate one effect from the other when influences (for positive or negative) are concurrent. Some activities may have synergistic or non-linear effects, the delineation of which goes beyond the scope of this work.

Exploring the influence of the period of record chosen could be important. Here, we used the full period of record available in analyses, as, even though human influences were highly unlikely to have been equal throughout the time period (particularly for the Thames and Lee catchments due to their >100-year record), it was felt that this would give the greatest representation of drought and drought termination metrics when using averages in the results. It was noted however that the period chosen can indeed influence the results obtained. For instance, when using only the 1951 – 2017 human-influenced and naturalised flow records for the Thames, the % change due to human influences in average drought termination rate was 36%, compared to just 4% using the period 1900 – 2017 (results not shown). It is likely that different record periods will have experienced different natural (i.e. climatic) and anthropogenic (i.e. abstraction activity) factors that will be driving differences in results. Further work is therefore needed to explore the use of different time periods in drought termination analyses to illustrate non-stationarity in human influences over time.

4.5 Application and future research directions

The framework used here to assess the termination phase allows application to any climatic/geographical region. This type of research (and further work) is invaluable for the formulation of adaptive responses to drought conditions, especially given that it is often human-influenced systems that we are most reliant upon for our water supply (Barker *et al*., 2016). Given that human influences are generally set to increase (Alcamo *et al.* 2003), attempting to quantify their impacts on aspects of drought is essential for improving knowledge on how to increase resilience and prepare for the drought challenges we face.

Longer drought recoveries have consequences for water companies under increasing pressure to meet potable water demands and ensure sustainability in their abstractions. The increased time available for the accumulation of pollutants (which might otherwise be present in streamflow in diffuse concentrations in non-drought conditions) during a longer termination phase may lead to water quality concerns when recovery and contaminant re-mobilisation does occur. Further to this, water companies have legal obligations to meet flow thresholds and regimes that maintain critical environmental thresholds for water-dependent species (EA, 2013). Biota often require frequent fluctuations between drought and non-drought (Zimmerman *et al*., 2017); a longer drought termination phase may alter the typical annual flow regime of a system in ways that prove unfavourable for certain species. If longer time periods are expected for termination, strategies in water resource management will have to adapt to minimise these impacts.

Understanding the link between drought termination duration and drought severity as a result of human water use and modifications enables water managers to balance supply and demand, based on current abstractions and the manner in which termination is likely to proceed. Knowledge of the rate at which the system recovers and the human influence on seasonal drought/termination patterns are therefore an inherent part of assessing these probabilities (Yuan *et al*., 2013). Information of this kind is also valuable for reservoir managers who have greater levels of control over stored resources (Návar and Lizárraga-Mendiola, 2016). Water managers may opt to implement short-, medium-, or long-term water-saving measures if they are aware of actions known to delay the recovery of the system (Bell *et al*., 2013). This also assists policy makers overseeing legislation (i.e. abstraction licences) with the aim of increasing sustainability and resilience to drought risks (DEFRA, 2013).

Knowledge of the seasonal cycle of water availability within a catchment is essential for those handling water resource management decisions. The findings of this study suggest that the timings associated with human-influenced drought termination could be predicted with more confidence than those in natural systems. Although it is arguably generally unfavourable to have fewer opportunities for drought termination, it could allow more robust decision-making if there is less uncertainty on its timing.

Work has begun exploring the predictability of drought recovery using global circulation models and large-scale meteorological forcings (Mo, 2011) or water-balance approaches (Bell *et al*., 2013). However, the significant impact of human activities is highly likely to be responsible in explaining some of the variation not captured by such climate/hydrological models. It is therefore important to consider the influence, non-stationarity and synergistic/antagonistic effects of our activities when working in this area.

The specific effect of management practices on the termination phase, including large-scale proactive measures (i.e. managed aquifer recharge) and other water saving technologies (Scanlon *et al*., 2016) merit investigation. The delineation of the impact of human activities where more than one is occurring in a catchment is yet another challenge that needs addressing (Parry *et al*., 2016b). A comparison between drought onset/development and termination phases may help reveal the significance of mechanisms or management strategies at work over the course of an event (Vernon-Kidd *et al*., 2017). As management practices change over short (daily, monthly) and longer (decadal) time periods, it would be interesting to test their impact on the termination phase as they evolve. This is no easy task however, as the type of information required (i.e. abstraction records) from governments/water managers is often sensitive or unreliable (Bromley *et al*., 2001; Novo *et al*., 2015)

Finally, the current sample size is small, therefore further work should aim to build on these results by adding more case studies and covering other human activities not included here, with a view to create a typology of termination characteristics under prevalent human influences. Examples include other reservoir purposes, urbanisation, deforestation and afforestation and other large-scale land-use changes that are yet to be studied in this context (Laurence and Williamson, 2001; Tallaksen and Van Lanen, 2004; Zhang *et al*., 2017). This will help to produce a deeper understanding of how important human activities are impacting the hydrological system, drought termination and ultimately help to guide water resource management in the future.

5. Summary and conclusions

Here we present the first study that analyses anthropogenic influences on the streamflow drought termination phase. Our example case studies in Europe have shown that human activities have a clear effect on drought termination characteristics. In response to human activities and compared to the naturalised situation, most case studies show a longer drought termination duration (by up to 275%), but a faster termination rate (with some over two orders of magnitude higher), due to an often more extreme maximum intensity in the human data than the naturalised. The time of year at which the termination phase begins and ends was observed to shift in systems under human influence, with more start and end months concentrated in a single season.

Furthering research in this topic will help gain a wider understanding on how human actions are modifying hydrological droughts and help to improve drought management policies. This is crucial for our understanding of how the transition from depleted to replenished water supplies is operationally handled (Hannaford *et al*., 2011; Bell *et al*., 2013) and should feature as a fundamental part of effective drought monitoring and early warning systems. Despite the increasing influence of human activities on water resources, their various impacts on drought termination were previously unknown. Further work should aim to build on current results by adding further case studies and covering other influential human activities not included here. Given the projected increase and non-stationarity of human influences, knowledge of this kind is subsequently invaluable for the formulation of adaptive responses to drought and managing the changing threat of water scarcity. This is extremely important as it is human-influenced systems that we are most reliant upon for water supply.

6. Appendix 1: Case studies and naturalisation methods

Svitata, Czech Republic

This catchment is located in eastern Czech Republic, underlain by sandstone aquifers suitable for drinking water extraction. Groundwater abstraction for drinking water therefore constitutes the main human influence and has increased considerably since 1975 (Tallaksen and Van Lanen, 2004). This significantly affects the catchment's flow regime. According to the Köppen-Geiger classification system (Kotek *et al*., 2006) the climate type is Dfb, with warm summers, a humid continental climate and no significant precipitation difference between seasons.

The BILAN lumped conceptual rainfall-runoff model (Kašpárek, 1998) was used by Van Loon and Van Lanen (2015) with the concepts of the observation-modelling framework (Van Loon and Van Lanen, 2013) to provide the naturalised data used here. The model solves the catchment-average water balance on a monthly timescale, calibrated using the observed discharge from the undisturbed period. Precipitation, air temperature and relative humidity data were used as input. Outputs were found to agree reasonably well with observations (Tallaksen and Van Lanen, 2004).

Bilina, Czech Republic

Located in Krušne mountains, north-west Czech Republic, the development of large-scale mining activities in the catchment meant that the Bilina's natural discharge was insufficient to meet the demands of growing industries and drinking water supply (Tallaksen and Van Lanen, 2004).

Consequently, the main human influence on the Bilina since 1960 has been the augmentation with water transported from a nearby river basin. The dominant climate type is Cfb, indicating a mild temperate oceanic climate.

The BILAN model was used by Van Loon and Van Lanen (2015) with the concepts of the observation-modelling framework (Van Loon and Van Lanen, 2013) to also provide the naturalised data for this catchment.

Ariège, France

The Ariège catchment is a mountainous sub-basin of the larger Garonne River basin in the Pyrenees. The river flow regime is influenced by a series of high-elevation reservoirs, relying mostly on snowmelt for recharge, whose main function is the production of hydro-electricity (Hendrickx and Sauquet, 2013). Water transfers (operating in both directions) between the Ebro River basin, located on the southern side of the Pyrenees in Spain, and the headwaters of the Ariège basin constitute a further human influence on the catchment. The climate classification of the basin is Cfb, meaning it experiences a mild temperate oceanic climate.

The naturalisation process removed the effects of the hydropower reservoir storage by taking account of reservoir levels and released discharges and adding them to the observed flow values (Vidal, 2017). The reconstructed time-series was then lagged to adjust for routing times between water bodies.

Upper-Guadiana, Spain

The Upper-Guadiana catchment is a headwater catchment of the Guadiana River, located in central Spain. It has a Mediterranean, semi-arid climate with very warm summers and mild winters (classes Csa, Csb and Bsk) (Van Loon and Van Lanen, 2013). The catchment has experienced severe multi-year meteorological droughts during the 1980-90s, however the presence of water stores (aquifer systems and wetlands) often attenuates these anomalies after periods of high precipitation, preventing further propagation through the hydrological system (Van Loon and Van Lanen, 2013). When hydrological drought does develop, events tend to be very long due to the combination of a semi-arid climate and slow response time to precipitation. Agriculture (mainly vineyards) is the dominant land use in the catchment, with human influence on the hydrological regime of the Upper-Guadiana being abstraction for irrigation and artificial drainage. Borehole abstractions increased by 244% between 1974-1988, causing dramatic drawdown in water tables.

Van Loon and Van Lanen (2013) developed the observation-modelling framework to quantify human influence in this catchment. For this, the HBV hydrological model was used to generate the naturalised data utilised in this research.

Thames, UK

The Thames catchment in south-east England is one of the driest regions in the country, experiencing a mild temperate oceanic climate (class Cfb). The gauging station at Kingston has one of the longest flow records in the UK. The basin overlies major chalk and oolite aquifers, which help sustain baseflow. This is a mixed influence catchment with several human activities influencing the hydrological regime simultaneously. Regulation from surface water, groundwater and reservoirs affect runoff, which is reduced by major abstractions for public water supply (PWS), industry and agriculture (CEH, 2019). Some effluent returns increase flows but overall this is substantially less than the effect of abstractions. Furthermore, the region has a high population and urban extent.

Naturalised flows are calculated with a naturalisation by decomposition method. Abstractions and discharges are monitored and reported by the parties involved, the volumes of which are used to adjust the gauged daily flow data on an average daily and monthly basis (Hammet, 2017).

Lee, UK

The gauging site for this catchment is located in the middle reaches of the River Lee, south-east England, downstream of the confluence with the River Stort. It is a pervious chalk basin, consisting of predominantly rural headwaters with significant urban growth in lower valley (CEH, 2019). Like the Thames, it has a mild temperate oceanic climate (Cfb). Flows are reduced by abstraction for PWS, industry and agriculture, and marginally increased by effluent returns. Considerable groundwater abstractions are exported from catchment (CEH, 2019). Naturalised flows are calculated with a naturalisation by decomposition method.

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Contributions

Contributed to conception and design: JM, SR, AVL, SP, and DW

Contributed to acquisition of data: SP, SR, and AVL

Contributed to analysis and interpretation of data: JM, SR, AVL

Drafted and/or revised the article: JM, with input of SR, SP, DW, and AVL

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Competing interests

The authors have declared that no competing interests exist.

Supplemental material

Data accessibility statement

The data used in this paper will be made available after an embargo period to allow further publication using this dataset.

Figures

Figure 1: Study catchments. Location of the six study catchments across Europe and the dominant human activity for each.

Figure 2: Definition of drought termination. Conceptual diagram of drought termination characteristics and definitions used.

Figure 3: Human-influenced and natural droughts and the timing of drought termination. Time-series and drought events identified (red areas) for a) Svitata and b) Bilina case studies. Relating histograms display the frequency (as % of drought events) of termination start (light blue) and end months (dark blue) for naturalised (top) and human-influenced (bottom) drought events.

Figure 3 (continued): Human-influenced and natural droughts and the timing of drought termination. Time-series and drought events identified (red areas) for c) Ariège and b) Upper-Guadiana case studies. Relating histograms display the frequency (as % of drought events) of termination start (light blue) and end months (dark blue) for naturalised (top) and human-influenced (bottom) drought events.

Figure 3 (continued): Human-influenced and natural droughts and the timing of drought termination. Time-series and drought events identified (red areas) for e) Thames and f) Lee case studies. Relating histograms display the frequency (as % of drought events) of termination start (light blue) and end months (dark blue) for naturalised (top) and human-influenced (bottom) drought events.

Figure 4: Correlation between drought termination duration and drought metrics. Relation between the % changes in a) drought termination duration and drought duration; b) drought termination duration and drought deficit; and c) drought termination duration and maximum intensity.

Figure 5: Correlation between drought termination rate and drought metrics. Correlations between the % changes in a) drought termination duration and drought duration; b) drought termination duration and drought deficit; and c) drought termination duration and maximum intensity.

Tables

Table 1. Summaries of case study details, their direct anthropogenic influences and naturalisation methods.

Table 2. Summaries of drought and drought termination metrics used in this study and their calculations.

Table 3. Percentage change results from naturalised to human-influenced data for drought and drought termination metrics. Any percentage change of 100% or above is in bold to highlight the high magnitude of change.