Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2018-215
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Discussion started: 25 April 2018

Using paired catchments to quantify the human influence on hydrological droughts

Sally Rangecroft[1], Anne F. Van Loon[1], Gemma Coxon[2], Jose Agustin Breña-Naranjo[3], Floris Van Ogtrop[4] & Henny A. J. Van Lanen[5]

[1] School of Geography, Earth and Environmental Sciences, University of Birmingham, Birmingham, UK

[2] School of Geographical Sciences, University of Bristol, UK

[3] Institute of Engineering, Universidad Nacional Autónoma de México, Mexico

[4] School of Life and Environmental Sciences, University of Sydney, Sydney, Australia

[5] Hydrology and Quantitative Water Management Group, Wageningen University, The Netherlands

Correspondence to: Anne Van Loon (a.f.vanloon@bham.ac.uk)

Abstract. Currently most of our understanding about the human influence on droughts at the catchment scale comes from modelling and typically not from observation data. Using observation data, a paired catchment comparison can be used to quantify the different between two similar catchments. Commonly used on control treatment experiments, paired catchments have been used recently in a more applied manner to analyse the effect of urbanization on flooding. In this study, we explore the paired catchment comparison approach as a possible way forward to quantify the influence of human activities on hydrological drought through observations. Using river discharge time series for drought analysis, the difference calculated in drought metrics (frequency, duration, deficit volumes) between the paired catchments is attributed to the human activity which is only present in the influenced catchment. Here we outline the methodological approach to quantifying this human influence on hydrological droughts and the requirements in catchment selection, as well as showcase the application using some example results from contrasting case studies in the UK and Australia with catchments heavily influenced by groundwater abstraction. Whilst the selection of the paired catchments must be done with rigorous criteria, this approach overcomes the impacts of climate variability in pre- and post-disturbance studies, and avoids assumptions considered when partly or fully relying on simulation modelling. We discuss important considerations for a successful analysis. This is the first application of this approach to quantify the human influence on hydrological droughts, demonstrating the use of this tool to study hydrology in our human-dominated world.

.

Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2018-215
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Discussion started: 25 April 2018

1 Introduction

In our human-modified era, the Anthropocene, human activities and actions have direct and indirect effects on the hydrological system (UNESCO, 2009; 2012; Montanari et al., 2013; McMillan et al., 2016). It is vital to understand how our activities are affecting the hydrological system to help us improve not only our understanding of our impacts and management of water resources, but also the representation of human activities in environmental modelling. One area where research has been limited, but has increased in recent years, is the understanding and quantification of how humans may influence hydrological droughts (Querner et al., 1997; Querner & Van Lanen, 2001; Van Lanen et al., 2004b) with recent calls for new tools and approaches to study the human influence on droughts (Van Loon et al., 2016a; 2016b). Here we use the definition of drought as a deficit in available water from 'normal' conditions (Wilhite & Glantz, 1985; Tallaksen & Van Lanen, 2004), with a focus on hydrological drought, which considers the deficit in streamflow.

Currently, using simulation data from hydrological modelling is one of the main ways in quantifying the human influence on droughts, because of its ability to isolate variables and input data generating natural and human influenced data for comparison (e.g. Querner et al., 1997; Van Loon & Van Lanen, 2013; 2015; Veldkamp et al., 2015; Wada et al., 2017; Wanders et al., 2017). Often this "scenario modelling" approach is done with large scale models (e.g. Veldkamp et al., 2015; Wada et al., 2017; Wanders et al., 2017), but these are not extensively calibrated or validated locally, and will therefore have large uncertainty. Furthermore, whilst the scientific community is seeking to add known human influences and decisions into hydrological models (Wada et al., 2017), current hydrological models do not tend to include all anthropogenic processes yet (Srinivasan et al., 2017).

To increase our understanding of these anthropogenic processes and interactions, we can explore observation data to help inform this progress. There are several methods used to explore the impacts of humans on hydrological droughts with more of a focus on observation data, such as the following three: (1) the observation modelling approach (here called "observed-naturalised") (e.g. Van Loon & Van Lanen, 2013) uses naturalised simulation data to compare to human influenced observation data. However, the simulated hydrological data also have uncertainties and a pre-disturbed period is needed for calibration to reduce those; (2) The "upstream-downstream" approach (Rangecroft et al., 2016) uses observation data only and uncertainty stems from the possible non-linear relationship between the upstream and downstream gauging stations; (3) Another approach using only observation data is the "pre-post-disturbance" approach (e.g. Liu et al., 2016), however the comparison of two different time periods makes it harder to separate the human influence from possible drought driven by climatic variability (e.g. decadal and multi-decadal) and non-stationarity due to climate change.

Instead, we suggest to use the same analysed period, but employing two different catchments to represent the natural and the human influenced situation, a "paired catchment" approach. An existing classic hydrological approach used to detect changes in catchment hydrology, the paired catchment analysis compares the flow regime of two catchments which have similar physical characteristics, to identify the impact of a disturbance on the flow regime (Hewlett, 1971; Bosch & Hewlett, 1982). The approach has been used successfully around the world to evaluate and quantify effects of land use change and treatment (e.g. afforestation, deforestation) on hydrology (e.g. water yields, floods and water quality) (Brooks et al., 2003; Brown et al., 2005; Folton et al., 2015), with fewer research studies investigating impacts on the hydrological phenomena of drought. We argue that this paired catchment approach could help quantify the human influence on drought and complement existing approaches.

Originally used with control treatment experiments, paired catchments have been more recently used in an applied manner by Prosdocimi et al. (2015) to analyse the effect of urbanization on flooding in the UK. In this paper, we explore the use of the paired catchment approach to assess the human influence on hydrological droughts. We present two case studies, from the UK and Australia, as example applications of this approach, generating knowledge about the human influence on droughts at the catchment scale from observation data. The case studies shown here both have abstraction of water in the human influenced catchment, but climate and geology are contrasting. Demonstrating the approach, we are adding to our tools for improved analysis and understanding of the human impact in the Anthropocene.

2 Methods

2.1 Paired catchment analysis

The paired catchment approach has been a predominant method for detecting the effects of disturbance on catchment scale hydrology (Zégre et al., 2010). Originating from the study of deliberate land treatment as disturbance (e.g. afforestation, deforestation) on water quantity and quality, the approach has been successfully used for many decades (Swank et al., 2001; Brooks et al., 2003; Brown et al., 2005; Putro et al., 2016). More recently, paired catchments have been used for studying existing disturbances and in long term studies over a longer time period (e.g. Prosdocimi et al., 2015). Starting as early as the 1920s (Bates, 1921), the use of paired catchments to study the impacts of forest treatments and management activities on water yields accelerated since the 1960s (e.g. Hewlett & Hibbert, 1961; Harris, 1977; Hornbeck et al., 1993; Robinson & Rycroft, 1999). Overall, most published studies have looked at land use change impacts on annual flow and flood peaks and assessing the magnitude of water yield change resulting from changes in vegetation (see review of Brown et al., 2005; Cornish, 1993; Bari et al., 1996; Best et al., 2003; Folton et al., 2015; Prosdocimi et al., 2015).

In the 1990s, some studies included low flows (e.g. Keppeler & Ziemer, 1990; Scott & Smith, 1997). It has been found that clearcut harvesting can lead to an increase in low flows (Keppeler & Ziemer, 1990), while land cover conversion from grasslands, shrublands and croplands to forests can cause a decrease of low flows (Scott & Smith, 1997; Farley et al., 2005). Previous low flow works also suggested that in watersheds located in dry regions streams were likely to completely dry up following afforestation, and that the streamflow regime in those watersheds would change from perennial to intermittent (Farley et al., 2005; Jackson et al., 2009). However research using the paired catchment approach to assess change in hydrological droughts due to land use and other human activities remains limited.

The basic concept of the method is to compare the flow regime of two nearby catchments with similar physical characteristics, one as a control ('natural') and the other as a disturbed catchment (also known as the 'treatment catchment' in some of the

Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2018-215
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Discussion started: 25 April 2018

literature). Comparing the same time periods allows for climatic variability to be accounted for in the analysis (Brown et al., 2005). Climate regimes, soil and geology conditions should be similar between the two catchments (Best et al., 2003; Brown et al., 2005; Folton et al., 2015), with the main difference being the disturbance in the human influenced catchment. Therefore, the identified differences in hydrology can then be attributed to the human influences in the disturbed catchment (Brown et al., 2005). In most paired-catchment studies, catchments are typically adjacent, although this is not always possible, but they tend to be in close proximity to help with the similarity of catchment characteristics and climate. For classic paired catchment treatment studies, pre-disturbance periods can be used for both catchments to ensure streamflow similarity, or to establish an existing relationship between the two catchments. However, hydrological impacts due to human activities are not usually intentional, and often human activities (e.g. urbanization, groundwater abstractions, reservoirs, etc) are not planned with monitoring for hydrological change in mind. Therefore data for pre-disturbance periods might not always be available, and it can also be difficult to pinpoint when human activity started to occur in the catchment and have an effect on streamflow. Subsequently, we have to look at utilising the approach with the post-disturbance data only for analysis in the Anthropocene.

2.2 Approach

Here we suggest using paired catchments to quantify the human influence on droughts. In this context, an undisturbed (natural) and a disturbed (human influenced, e.g. water abstraction, urbanisation, reservoirs) catchment are used, and the analysis focuses on the effect on hydrological drought metrics (e.g. drought durations and deficit volumes), rather than on water yield or low flows in general. Here we outline the important elements for the approach, such as the characteristics involved in the catchment selection process, the data required, the drought analysis, and the calculation for quantifying the human influence.

2.3 Catchment selection

One of the most critical requirements for a successful paired catchment comparison is that the catchment characteristics are as similar as possible, except for the human disturbance which is being quantified. Relevant catchment characteristics could include precipitation, temperature (or potential evapotranspiration), land use, catchment area, elevation, geology, soils and how similar these characteristics should be for a paired catchment analysis will vary depending on the hydrological extreme of interest (e.g. floods, droughts) and the dominant characteristics that control hydrological response in that region (e.g. potential evapotranspiration may be more important in drier, hotter climates; Oudin et al., 2010). There is little literature on the acceptable differences between the paired catchments, so we here give some guidance on which characteristics are important for this application of the approach, and how these could be assessed.

For drought studies, precipitation, potential evapotranspiration (PET), soils and geology are considered to be the most important characteristics (Table 1; Van Lanen et al., 2004a; 2013; Stoelzle et al., 2014) to ensure similar meteorological conditions and hydrological response in both catchments.

It is often quite difficult to find paired catchments with exactly the same characteristics so it is necessary to put some limits on what is deemed as acceptable for pairing. Consequently, in this study, catchments were considered to be suitable for pairing if

differences in average annual precipitation and potential evapotranspiration were within ±10% and the catchments had the same geology classification/typology (see Table 1). It is also important to check precipitation variability as well as annual values, as the annual averages could be masking very different distributions of precipitation which would then result in different meteorological droughts in the catchments. This check can be done by plotting the precipitation values for both catchments on the annual and monthly time scale to see their similarities and differences. Case studies where precipitation distributions between the catchments had linear regression slopes and R^2 values of less than 0.5 were excluded from the paired catchment analysis. Geology/soils have to be checked on their responsiveness, i.e. flashy versus slow response to precipitation, implying that the geology and soils need to be translated based on expert knowledge. To enable the attribution of change to the known human influence, the catchment selection also requires a singular human influence if possible, or dominant human influence.
For our application of the paired catchment analysis there are some catchment characteristics which are not appropriate for the catchment selection process. Base Flow Index (BFI) calculated from discharge records is not used as a catchment selection characteristic because the BFI value in a human influenced catchment might be affected by the human activity. Similarity of BFI values can only be tested if reliable data from a pre-disturbance period is available. Proximity of catchments is also not a set catchment selection criterion because neighbouring catchments can actually have very different geology or precipitation totals (e.g. due to rain shadow effect), however close by catchments are a good starting point in the search for similar catchments.

2.4 Data requirements

Ideally, observation data of precipitation and discharge records for a minimum of 30 years should be used, with limited missing data (< 5%) so that robust statistics can be computed for hydrological extremes (McKee et al., 1993; Rees et al., 2004). Information on catchment characteristics (in this case annual precipitation and geology) and the type of human activity in the human influenced catchment are also required.
Although the paired catchment approach is most commonly used with annual data, it has also been used with monthly data (Bari et al., 1996; Brown et al., 2005). Drought analysis is normally conducted on the daily or monthly time step (e.g. Hisdal et al., 2004; Fleig et al., 2006; Van Loon & Van Lanen, 2012). Therefore, here we use monthly data for the paired catchment analysis.

2.5 Drought analysis

For each catchment, drought events and their metrics were identified with the commonly used drought analysis method, the threshold level method (Yevjevich, 1967; Tallaksen & Van Lanen, 2004; Van Loon, 2015). Drought event metrics such as timing (start date, end date), duration (months) and deficit volumes (mm) were extracted from the observation data time series. These metrics were then compared within each paired catchment, allowing the difference due to the human influence to be estimated (Figure 1).

The threshold level method defines drought events when data (streamflow) are below a specified threshold (Yevjevich, 1967; Hisdal & Tallaksen, 2000; Hisdal et al., 2004; Fleig et al., 2006). Here the 80th percentile was used as the threshold, meaning that 80% of the time discharge is above the threshold. The 80th percentile is a commonly used threshold to identify drought events (Hisdal & Tallaksen, 2000; Fleig et al., 2006; Van Huijgevoort et al., 2012; Van Loon & Van Lanen, 2012). The threshold can be fixed or variable, but we used the variable threshold to incorporate seasonality into the threshold (Hisdal & Tallaksen, 2000; Hisdal et al., 2004; Fleig et al., 2006; Heudorfer & Stahl, 2016). Drought events of only 1 month have been excluded from the analysis process so that drought events are longer than the time step of the threshold.

To enable quantification of the human influence, the threshold was generated from the natural catchment time series (Figure 1; Van Loon & Van Lanen, 2013), therefore excluding any human influence on the threshold. This natural threshold was then applied to both catchments for the drought analysis (Figure 1), with the resulting differences between the pair therefore being attributed to the human influence (Figure 1; Prosdocimi et al., 2015).

Chronological pairing of flooding events is known to be difficult because storms do not always coincide in time, duration, intensity or spatial extents between the paired catchments (Zégre et al., 2010). Drought on the other hand does not occur on such a small and localised spatial scale and short temporal scale, therefore this is less of an issue. However, it can still be limiting to compare one off events (e.g. in the case of droughts ending by localised rainstorms), therefore here we have analysed the changes in average and maximum drought metric over a longer time period rather than specific drought events.

2.6 Estimation of the human impact on drought characteristics

The drought metrics of duration (mean and maximum), deficit volumes (mean and maximum), frequency of drought events, and total number of months spent in drought were obtained from the drought analysis for each paired catchment. To calculate the human influence between the two catchments, the difference between the natural catchment drought metrics and the human influenced catchment metrics (Figure 1) was established using the following Eq. (1):

$$\textit{Percentage increase due to the human influence (\%)} = \left[\frac{(\textit{Human} - \textit{Natural})}{\textit{Natural}}\right] * 100 \qquad (1)$$

3. Application of the paired catchment approach

Here we present results from two case studies to show the application of the paired catchment approach to quantify the human influence on hydrological drought metrics. We are demonstrating the approach and focusing on the discussion of its applicability.

3.1 Case studies

The two case studies shown here (Figure 2) were chosen because both have groundwater abstraction, but contrasting climate and geology. The UK case study has a temperate maritime climate and a slowly responding catchment, and the Australian paired catchment has a semi-arid climate and a flashier catchment. These case studies were chosen based on the availability of data required for the assessment and analysis, including information on the human activities occurring in the catchments.
Table 2 outlines the main information about the two paired catchments. For this application, we used observed discharge data (standardised by catchment area, in mm/month). Precipitation data (mm/month) was used to check the similarity of average annual precipitation (within ± 10%) and distribution of monthly precipitation (Table 1 & 2). For the UK case study, discharge time series and geology information were sourced from the National River Flow Archive (NRFA, 2017) and precipitation data was obtained from CEH-GEAR (Keller et al., 2015). For the Australian case study, discharge and precipitation data and geology information were sourced from the Australian NSWs WaterInfo (NSW, 2017).

3.2 UK paired catchments: Kennet and Dun

It is known that water abstractions affect streamflow of the river Kennet, a catchment in Southern England (Dunbar et al., 2002). The Kennet is a catchment underlain by chalk and is reported to be predominately rural, with a market town close to outfall (NRFA, 2017). The Kennet was paired with a similar catchment nearby as its natural pair, the Dun (Figure 2), due to its similarity in catchment characteristics (Table 2). The Dun is also a chalk dominated, rural catchment with an annual rainfall total only 1% less than the Kennet. Importantly, abstractions and discharges are reported to be of minor significance at the Dun catchment (NRFA, 2017). Both catchments have very low urban extent (<3%) (NRFA, 2017). The observation data available for both catchments ran from 1973 to 2013 with no missing data, covering a number of important drought events in the UK.
Drought analysis using the paired catchment approach showed an aggravation in all drought metrics due to the human activity, especially in the total number of months spent in drought, the maximum drought duration and deficit volumes, and the average deficit volumes (Figure 3; Table 3). Both catchments clearly show the main drought events of the UK, including the 1976, the 1991-1992 and 2011-12 droughts, but these drought events were worsened in the human influenced catchment (Figure 3). Also, a number of human-induced droughts occurred in periods when the natural system did not experience similar hydrological droughts (Figure 3).

3.3 Australian paired catchments: Cox and Cockburn

The Cox catchment in south-eastern Australia has heavy groundwater abstraction for irrigation (Ivkovic et al., 2014). For the paired catchment analysis, the natural catchment, Cockburn, was chosen based on its similarity in precipitation and geology (Table 2) and its proximity (Figure 2). BFI for the natural catchment is much lower than that of the UK natural catchment, showing that the Australian catchments are responding faster to precipitation (Table 2). Observation data was available from 1982 – 2013, with no missing data.

Results also showed an overall aggravation of drought metrics due to the groundwater abstraction in the human influenced catchment, especially for the total number of months spent in drought and the average deficit (Figure 4, Table 4). However, it does not seem to affect the maximum drought event characteristics (Table 4) because during these rare events the flow is zero in both cases. The well documented Millennium Drought (2001 – 2009; Van Dijk et al., 2013) is shown clearly as a series of hydrological drought events in the human influenced catchment, whereas it was not as persistent in the natural catchment (Figure 4).

4. Discussion

As a scientific community we need to improve our understanding of the effect of human processes on hydrology and quantify the two way interactions to be able to characterise, model and manage them (Srinivasan et al., 2017). These processes can only be fully explored through observations. Here we have demonstrated that a paired catchment approach is a suitable tool using observation data to assess and quantify the human influence on hydrological droughts. There are limitations to this approach, as any observation and/or modelling based approach has uncertainties. Modelling methods for quantifying the human influence have uncertainties associated to input data, parameters and model structure, which often does not include human processes (Wagener et al., 2004; Kreibich et al., 2017; Srinivasan et al. 2017), and observation-based methods have uncertainties with regards to temporal or spatial resolution and data quality.

As discussed in this paper, for an effective paired catchment analysis it is important for the catchment properties to be as similar as possible, enabling isolation of the human influence. In this study, we selected the catchment pairs based on three different metrics: precipitation, geology and PET (Table 1). Paired catchments in this study were chosen manually using expert judgement; however, recent advances in catchment classification and similarity frameworks (see Hrachowitz et al, 2013) could be an alternative because these might provide a more objective and automated method to select paired catchments. Nevertheless, currently local knowledge is still a highly valuable part of catchment selection.

Here we focused on geology and precipitation as these two characteristics have been found elsewhere to be the largest constraints on successful analysis of droughts (Van Lanen et al., 2004a; 2013; Haslinger et al., 2014; Stoelzle et al., 2014; Van Loon & Laaha, 2015). In particular, we argue that differences in geology are more important for low flow studies and droughts than for floods and annual flow analysis, because of the importance of catchment storage in the catchment response to precipitation and the drought propagation process (Van Lanen et al., 2013; Van Loon & Laaha, 2015; Barker et al., 2016). Differences in geology affect storage and response of catchments, and therefore response to meteorological drought events in one geology type could be very different to another, making it difficult to distinguish the human influence from the geological differences.

With regards to precipitation, similarity in precipitation is important as it is the driving meteorological factor. Both precipitation variability and annual averages should be similar for the paired catchments (Table 1). Firstly, it is important that the total precipitation inputs are similar for both catchments because of the cross use of the natural catchment threshold. Significantly higher or lower precipitation in the natural catchment results in higher or lower discharge, which reduces the transferability of the threshold to the human-influenced catchment. We suggest a maximum difference of 10%. Precipitation distribution may be very different even if total average values are similar, meaning that meteorological drought events experienced by the two catchments could be different. Ideally, the monthly and annual precipitation records of both catchments are also similar, which can be checked with the linear regression coefficient and R^2 values. Catchment pairing where precipitation distributions with linear regression slopes and R^2 values are less than 0.5 should be excluded from the paired catchment analysis.

Moreover, it is important to make sure that there are not multiple human activities influencing streamflow in the human-influenced catchment. Attribution of differences between the paired catchments and understanding of the effect of human activities can be done best when isolating the human influence under study. Here the focus was on the human activity of groundwater abstraction, but other human influences can be analysed using the paired catchment approach, such as land use change, water addition, or water infrastructure.

Designed paired catchment experiments usually include a specific pre-disturbance period for calibration and to assess the similarity of the catchments. Even when the catchments are subject to the same climatic variability, their hydrological response to an event may differ due to natural differences between the pairs (Folton et al., 2015), therefore a pre-disturbance period can possibly offer a quantification of their differences, e.g. through a regression equation (Hornbeck et al., 1993; Bari et al., 1996). However, generally this does assume a linear relationship between the pairs, which is a very crude assumption. Furthermore, a pre-disturbance period might not be available for paired catchments when they are not planned treatments, for example it was not possible with the applications in this study. Furthermore, changes in groundwater and river regimes that are not anticipated may not have a monitored undisturbed period. Therefore we need to test the applicability of paired catchments without a pre-disturbance period to expand assessment beyond planned treatments.

There are some challenges which remain specific to the paired catchment analysis. Firstly, it can be very difficult to find a natural pair for a human influenced catchment where the human influence is the only difference. Keeping a close proximity between the pairs can often help to reduce differences in geology and precipitation, however groundwater abstractions are known to impact the surrounding areas, beyond the catchment boundary, therefore neighbouring catchments might not be regarded as natural and should not be used in a paired catchment analysis of the effect of groundwater abstraction. Instead, we suggest to compromise on another selection criterion (Table 1), such as precipitation, to locate a suitable natural catchment.

A second challenge, which is relevant for all observation-based methods, is data availability. Data availability and quality can severely affect the success of a catchment pairing or analysis. There is also the need for information on the type and extent of human disturbance within the data, which may not always be available or known.

The application in this paper is the first use of paired catchments to quantify the human influence on hydrological droughts, but it shows the potential of the method as a standalone approach, or to compliment other existing methods (e.g. simulation and observation-modelling approaches). One possible way forward could be to use published paired catchments, but to focus the analysis on droughts rather than annual hydrological regime to assess how treatments of land cover change (e.g. deforestation, afforestation) have impacted hydrological droughts. These existing datasets have pre-disturbed time periods, and catchment selection has already been done rigorously. Another way would be to analyse other direct human activities such as urbanisation and the building of reservoirs.

5. Concluding remarks

In our human-dominated world we need to find ways to use our tools and methods to study the human influence on hydrology. Here we show the first application of the paired catchment approach to quantify the human influence on hydrological droughts. We discussed how the selection of the paired catchments must be done with rigorous criteria (e.g. similar precipitation/climate, geology), and identified the advantages and limitations of the approach. The main advantage of the approach is that it compares the same time periods, therefore allowing climatic variability to be accounted for in the analysis. Furthermore, the approach uses catchment scale observation data, allowing us to gain information on the catchment level, with all of the catchment processes included. The other advantage to using an observation-only approach is that human actions and feedbacks are represented in the data, whereas most hydrological models currently do not include all anthropogenic processes yet. Whilst there are some uncertainties with regards to input data and catchment similarities, it is important to note that these uncertainties are similar to existing methods used to quantifying the human influence on hydrological drought.

Here we showed how the paired catchments approach, originally developed for treatment studies, and usually used for quantifying the impact of land use change on average discharge, could be used to look specifically at the human impact on droughts. We have used the method to analyse the impact of groundwater abstraction in contrasting climate and geology settings. The example case studies analysed of the UK and Australia clearly show an aggravation of drought due to the human activity compared to the natural catchment. However differences in the human influence between the two case studies are seen, highlighting the importance of further analysis into how humans influence hydrological droughts. Paired catchments could be used to further investigate the impact of other human activities on hydrological droughts using observation data. Through an increased understanding of how human activities influence droughts, this knowledge can then be used for water resource management and for improving hydrological modelling.

Acknowledgements

Sally Rangecroft and Anne Van Loon were supported by Rubicon NWO grant “Adding the human dimension to drought” (reference number: 2004/08338/ALW). Gemma Coxon was supported by NERC MaRIUS: Managing the Risks, Impacts and Uncertainties of droughts and water Scarcity, grant number NE/L010399/1. We thank Wouter Coomans (Wageningen

University) for collating and analysing data from the Australian case study. The research also contributed to the European Union funded H2020 project ANYWHERE (contract no. 700099). It is part of the programme of the Wageningen Institute for Environment and Climate Research (WIMEK-SENSE) and it supports the work of the UNESCO-IHP VIII FRIEND-Water programme and the IAHS Panta Rhei decade. Drought analysis R code is available upon request.

References

Bari, M. A., Smith, N., Ruprecht, J. K., Boyd, B. W. Changes in streamflow components following logging and regeneration in the Southern forest of Western Australia. Hydrol Process, 10: 447-461, doi: 10.1002/(SICI)1099-1085(199603)10:3<447::AID-HYP431>3.0.CO;2-1, 1996

Barker, L. J., Hannaford, J., Chiverton, A., Svensson, C. From meteorological to hydrological drought using standardised indicators, Hydrol Earth Syst Sc, 20: 2483–2505, doi: 10.5194/hess-20-2483-2016, 2016

Bates, C.G. First results in the streamflow experiment, Wagon Wheel Gap, Colorado. J Forest, 19(4): 402-408, 1921

Best, A., Zhang, L., McMahon, T., Western, A., Vertessy, R. A critical review of paired catchment studies with reference to seasonal flows and climatic variability. Murray-Darling Basin Commission. CSIRO Land and Water Technical Report 25/03, 2003

Bosch, J. M. & Hewlett, J. D. A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration. J Hydrol, 55: 3-23, doi: 10.1016/0022-1694(82)90117-2, 1982

Brooks, A. P., Brierley, G. J. & Millar R. G. The long-term control of vegetation and woody debris on channel and flood-plain evolution: insights from a paired catchment study in southeastern Australia. Geomorphology, 51(1-3): 7-29, doi: 10.1016/S0169-555X(02)00323-9, 2003

Brown, A. E., Zhang, L., McMahon, T. A., Western, A. W., Vertessy, R. A. A review of paired catchment studies for determining changes in water yield resulting from alterations in vegetation. J Hydrol, 310: 28-61, doi:10.1016/j.jhydrol.2004.12.010, 2005

Cornish, P. M. The effect of logging and forest regeneration on water yields in a moist eucalypt forest in New South Wales, Australia. J Hydrol, 150: 301-322, 10.1016/0022-1694(93)90114-O, 1993

Dunbar, M., Booker, D., Straford, C., Latimer, P., Rogerson, H., Bass, J., Dawson, H., Gozlan, R., Welton, S., Ash, J., Fenn, T., Postle, M. Heavily Modified Waters in Europe – Case Study of the River Kennet, Environment Agency of England & Wales and the UK Government Department for Food, Environment and Rural Affairs, England and Wales (http://www.oieau.org/eaudoc/system/files/documents/39/195769/195769_doc.pdf), 2002

Farley, K. A., Jobbagy, E. G. & Jackson, R. B. Effects of afforestation on water yield: a global synthesis with implications for policy, Glob Change Biol 11: 1565-1576, doi: 10.1111/j.1365-2486.2005.01011.x, 2005

Fleig, A. K., Tallaksen, L. M., Hisdal, H., Demuth, S. A global evaluation of streamflow drought characteristics. Hydrol Earth Syst Sc, 10: 535-552, 10:535–552, doi:10.5194/hess-10-535-2006, 2006

Folton, N., Andréassian, V. & Duperray, R. Hydrological impact of forest-fire from paired-catchment and rainfall-runoff modelling perspectives. Hydrolog Sci J, 60(7-8): 1213-1224, doi: 10.1080/02626667.2015.1035274, 2015

Harris, D. D. Hydrologic changes after logging in two small Oregon Coastal watersheds. US Geological Survey Water-Supply Paper. 2037, 1977

Haslinger, K., Koffler, D., Schöner, W., Laaha, G. Exploring the link between meteorological drought and streamflow: Effects of climate-catchment interaction, Water Resour Res, 50(3): 2468-2487, doi: 10.1002/2013WR015051, 2014

Heudorfer, B. & Stahl, K. Comparison of different threshold level methods for drought propagation analysis in Germany. Hydrol Res, 47(4), doi: 10.2166/nh.2016.258, 2016

Hewlett, J. D. Comments on the catchment experiment to determine vegetal effects on water yield, Water Resour Bull, 7(2): 376-381, doi: 10.1111/j.1752-1688.1971.tb05920.x, 1971

Hewlett, J. D. & Hibbert, A. R. Increases in water yield after several types of forest cutting. IAHS Bulletin, Vol. 6, IAHS, Wallingford: 5-17, 1961

Hisdal, H. & Tallaksen, L. M. Drought Event Definition. Technical Report No. 6: Assessment of the Regional Impact of Droughts in Europe. Department of Geophysics, University of Oslo, Norway, 2000

Hisdal, H., Tallaksen, L. M., Clausen, B., Peters, E., Gustard, A. Drought characteristics. In Tallaksen, L. M. & Van Lanen, H. A. J. (Eds.). Hydrological drought: processes and estimation methods for streamflow and groundwater. Developments in Water Science. 48. p. 139-198. Elsevier, 2004

Hornbeck, J. W., Adams, M. B., Corbett, E. S., Verry, E.S., Lynch, J. A. Long-term impacts of forest treatments on water yield: a summary for northeastern USA. J Hydrol, 150(2-4): 323-344, doi: 10.1016/0022-1694(93)90115-P, 1993

Hrachowitz, M., Savenije, H. H. G., Blöschl, G., McDonnell, J. J., Sivapalan, M., Pomeroy, J. W., Arheimer, B., Blume, T., Clark, M. P., Ehret, U., Fenicia, F., Freer, J. E., Gelfan, A., Gupta, H. V., Hughes, D. A., Hut, R. W., Montanari, A., Pande, S., Tetzlaff, D., Troch, P.A., Uhlenbrook, S., Wagener, T., Winsemius, H. C., Woods, R. A., Zehe, E., Cudennec, C. A decade of Predictions in Ungauged Basins (PUB) - a review, Hydrolog Sci J, 58(6): 1198-1255, doi: 10.1080/02626667.2013.803183, 2013

Ivkovic, K. M., Croke, B. F. W. & Kelly, R. A. Overcoming the challenges of using a rainfall-runoff model to estimate the impacts of groundwater extraction on low flows in an ephemeral stream. Hydrol Res, 45(1): 58-72, 2014

Jackson, R. B., Jobbagy, E. G. & Nosetto, M. D. Ecohydrology in a human-dominated landscape, Ecohydrology, 2: 383–389, doi: 10.1002/eco.81, 2009

Keller, V. D. J., Tanguy, M., Prosdocimi, I., Terry, A., Hitt, O., Cole, S. J., Fry, M., Morris, D. G., Dixon, H. CEH-GEAR: 1 km resolution daily and monthly areal rainfall estimates for the UK for hydrological and other applications. Earth Syst Sci Data, 7: 143-155, doi: 10.5194/essd-7-143-2015, 2015

Keppeler, E. & Ziemer, R. Logging effects on streamflow: water yield and summer low flows at Caspar Creek in northwestern California, Water Resour Res, 26(7): 1669-1679, doi: 10.1029/WR026i007p01669, 1990

Kreibich, H., Krueger, T., Van Loon, A. F., Mejia, A., Junguo Liu, J., McMillan, H., Castellarin, A. Scientific debate of Panta Rhei research – how to advance our knowledge of changes in hydrology and society?, Hydrolog Sci J, 62(3): 331-333, doi: 10.1080/02626667.2016.1150032, 2017

Liu, Y., Ren, L., Zhu, Y., Yang, X., Yuan, F., Jiang, S., Ma, M. Evolution of Hydrological Drought in Human Disturbed Areas: A Case Study in the Laohahe Catchment, Northern China. Adv Meteorol, doi: 10.1155/2016/5102568, 2016

McKee, T. B., Doesken, N. J. & Kleist, J. The Relationship of Drought Frequency and Duration to Time Scales. Proceedings of the Eighth Conference on Applied Climatology, American Meteorological Society, Boston, 179-184, 1993

McMillan, H., Montanari, A., Cudennec, C., Savenije, H., Kreibich, H., Krueger, T., Liu, J., Mejia, A., Van Loon, A. F., Aksoy, H., Di Baldassarre, G., Huang, Y., Mazvimavi, D., Rogger, M., Sivakumar, B., Bibikova, T., Castellarin, A., Chen, Y., Finger, D., Gelfan, A., Hannah, D. M., Hoekstra, A. Y., Li, H., Maskey, S., Mathevet, T., Mijic, A., Pedrozo Acuña, A., Polo, M. J., Rosales, V., Smith, P., Viglione, A., Srinivasan, V., Toth, E., van Nooyen R. & Xia, J. Panta Rhei 2013–2015: global perspectives on hydrology, society and change, Hydrolog Sci J 61(7): 1174-1191, doi: 10.1080/02626667.2016.1159308, 2016

Montanari, A., Young, G., Savenije, H. H. G., Hughes, D., Wagener, T., Ren, L. L., Koutsoyiannis, D., Cudennec, C., Toth, E., Grimaldi, S., Blöschl, G., Sivapalan, M., Beven, K., Gupta, H., Hipsey, M., Schaefli , B., Arheimer , B., Boegh, E., Schymanski , S.J., Di Baldassarre, G., Yu, B., Hubert, P., Huang, Y., Schumann, A., Post, D., Srinivasan, V., Harman, C., Thompson, S., Rogger, M., Viglione, A., McMillan, H., Characklis, G., Pang, Z. & Belyaev, V. (2013) "Panta Rhei – Everything Flows": Change in hydrology and society – The IAHS Scientific Decade 2013–2022, Hydrolog Sci J, 58(6): 1256-1275, 10.1080/02626667.2013.809088, 2013

NRFA, National River Flow Archive, UK, http://nrfa.ceh.ac.uk 2017

NSW, New South Wales Government, Australia, http://waterinfo.nsw.gov.au/ 2017

Oudin, L., Kay, A., Andréassian, V., Perrin, C. Are seemingly physically similar catchments truly hydrologically similar? Water Resources Research, 46, W11558, doi: 10.1029/2009WR008887, 2010.

Prosdocimi, I., Kjeldsen, T. S. and Miller, J. D. Detection and attribution of urbanization effect on flood extremes using nonstationary flood-frequency models. Water Resour Res, 51(6): 4244-4262, doi: 10.1002/2015WR017065, 2015

Putro, B., Kjeldsen, T. R., Hutchins, M. G., Miller, J. An empirical investigation of climate and land-use effects on water quantity and quality in two urbanising catchments in the southern United Kingdom. Sci Total Environ, 548-549: 164-172. doi:10.1016/j.scitotenv.2015.12.132, 2016

Querner, E.P. & Van Lanen, H. A. J. Impact assessment of drought mitigation measures in two adjacent Dutch basins using simulation modelling. J Hydrol, 252: 51-64, 2001

Querner, E.P., Tallaksen, L.M., Kašpárek, L., Van Lanen, H. A. J. Impact of land-use, climate change and groundwater abstraction on streamflow droughts basin using physically-based models. In: A. Gustard et al. (Eds.), FRIEND'97-Regional Hydrology: Concepts and Models for Sustainable Water Resource Management, 246: 171-179, 1997

Rangecroft, S., Van Loon, A. F., Haureira, H., Verbist, K., Hannah, D. M. Multi-method assessment of reservoir effects on hydrological droughts in an arid region. Earth Syst Dynam Discussion, doi: 10.5194/esd-2016-57, 2016

Rees, G., Marsh, T. J., Roald, L., Demuth, S., Van Lanen, H. A. J., Kašpárek, L. Hydrological Data, Chapter 4. In: In Tallaksen, L.M. & Van Lanen, H. A. J. (Eds.). Hydrological drought: processes and estimation methods for streamflow and groundwater. Developments in Water Science. 48. p. 99-138. Elsevier, 2004

Robinson, M. & Rycroft, D.W. The impact of drainage on streamflow. Chapter 23 in: Skaggs, W. & van Schilfgaarde, J. (eds) Agricultural Drainage. Agronomy. Monograph 38. American Society of Agronomy, Madison, Wisconsin. pp 753-786, 1999

Scott, D. F. & Smith R. E. Preliminary empirical models to predict reductions in annual and low flows resulting from afforestation. Water SA, 23: 135–140, 1997

Srinivasan, V., Sanderson, M., Garcia, M., Konar, M., Blöschl, Sivapalan, M. Prediction in a socio-hydrological world. Hydrol Sci J, 62(3): 338-345, doi: 10.1080/02626667.2016.1253844, 2017

Stoelzle, M., Stahl, K., Morhard, A., Weiler, M. Streamflow sensitivity to drought scenarios in catchments with different geology, Geophys Res Lett, 41: 6174-6183, doi: 10.1002/2014GL061344, 2014

Swank, W. T., Vose, J. M. & Elliott, K. J. Long-term hydrologic and water quality responses following commercial clearcutting of mixed hardwoods on a southern Appalachian catchment. Forest Ecol Manag, 143(1-3): 163-178, 2001

Tallaksen, L. M. & Van Lanen, H. A. J. (Eds.) Hydrological drought: processes and estimation methods for streamflow and groundwater. In: Developments in Water Science; 48, The Netherlands, Elsevier Science B.V., Amsterdam, The Netherlands, 2004

UNESCO. Water in a changing world. The United Nations World Water Development Report 3, World Water Assessment Programme, UNESCO, Paris, France, 2009

UNESCO. Water security: responses to local, regional, and global challenges, Strategic Plan, International Hydrological Programme VIII, IHP-VIII (2014-2021), UNESCO, Paris, France, 2012

Van Dijk, A. I. J. M., Beck, H. E., Crosbie, R. S., de Jeu, R. A. M., Liu, Y. Y., Podger, G. M., Timbal, B., Viney, N. R. The Millennium Drought in southeast Australia (2001 – 2009): Natural and human causes and implications for water resources, ecosystems, economy and society. Water Resour Res, 49: 1040-1057, doi: 10.1002/wrcr.20123, 2013

Van Huijgevoort, M. H., Hazenberg, P., van Lanen, H. A. J., Uijlenhoet, R. A generic method for hydrological drought identification across different climate regions. Hydrol Earth Syst Sc, 16: 2437 – 2451, doi: 10.5194/hess-16-2437-2012, 2012

Van Lanen, H. A. J., Fendeková, M., Kupczyk, E., Kasprzyk, A., Pokojski, W. Flow Generating Processes, Chapter 3. In: Tallaksen, L.M., and Van Lanen, H.A.J. (Eds.) (2004) Hydrological Drought. Processes and Estimation Methods for Streamflow and Groundwater. Developments in Water Science, 48, Elsevier Science B.V., pg. 53-96, 2004a

Van Lanen, H. A. J., Kašpárek, L., Novický, O., Querner, E. P., Fendeková, M., Kupczyk, E. Human Influences, Chapter 9. In: Tallaksen, L.M. & van Lanen, H.A.J. (Eds.) (2004) Hydrological Drought. Processes and Estimation Methods for Streamflow and Groundwater. Developments in Water Science, 48, Elsevier Science B.V., pg. 347-410, 2004b

Van Lanen, H. A. J., Wanders, N., Tallaksen, L. M., and Van Loon, A. F. Hydrological drought across the world: impact of climate and physical catchment structure. Hydrol Earth Syst Sc, 17: 1715–1732, doi: 10.5194/hess-17-1715-2013, 2013

Van Loon, A. F. Hydrological drought explained. WIREs Water, 2(4): 359-392, doi: 10.1002/wat2.1085, 2015

Van Loon, A. F. & Laaha, G. Hydrological drought severity explained by climate and catchment characteristics. J Hydrol, 526: 3-14, doi: 10.1016/j.jhydrol.2014.10.059, 2015

Van Loon, A. F. & Van Lanen, H. A. J. A process-based typology of hydrological drought. Hydrol Earth Syst Sc, 16: 1915-1946, doi: 10.5194/hess-16-1915-2012, 2012

Van Loon, A. F. & Van Lanen, H. A. J. Making the distinction between water scarcity and drought using an observation-modeling framework. Water Resour Res, 49: 1483–1502, doi: 10.1002/wrcr.20147, 2013

Van Loon, A. F. & Van Lanen, H. A. J. Testing the observation-modelling framework to distinguish between hydrological drought and water scarcity in case studies around Europe. European Water, 49: 65-75, 2015

Van Loon, A. F., Gleeson, T., Clark, J., Van Dijk, A. I. J. M., Stahl, K., Hannaford, J., Di Baldassarre, G., Teuling, A. J., Tallaksen, L. M., Uijlenhoet, R., Hannah, D. M., Sheffield, J., Svoboda, M., Verbeiren, B., Wagener, T., Rangecroft, S., Wanders, N., Van Lanen, H. A. J. Drought in the Anthropocene. Nat Geosci, 9: 89-91, doi: 10.1038/ngeo2646, 2016a

Van Loon, A. F., Gleeson, T., Clark, J., Van Dijk, A. I. J. M., Stahl, K., Hannaford, J., Di Baldassarre, G., Teuling, A. J., Tallaksen, L. M., Uijlenhoet, R., Hannah, D. M., Sheffield, J., Svoboda, M., Verbeiren, B., Wagener, T., Rangecroft, S., Wanders, N., Van Lanen, H. A. J. Drought in a human-modified world: reframing drought definitions, understanding and analysis approaches. Hydrol Earth Syst Sc, 20(9): 3631–3650, 10.5194/hess-20-3631-2016, 2016b

Veldkamp, T. I. E., Wada, Y., de Moel, H., Kummuc, M., Eisner, S., Aerts, J. C. J. H., Ward, P. J. Changing mechanism of global water scarcity events: Impacts of socioeconomic changes and inter-annual hydroclimatic variability, Global Environ Chang, 32, 18–29, doi: 10.1016/j.gloenvcha.2015.02.011, 2015

Wada, Y., Bierkens, M. F. P., De Roo, A., Dirmeyer, P.A., Famiglietti, J.S., Hanasaki, N., Konar, M., Liu, J., Müller-Schmied, H., Oki, T., Pokhrel, Y., Sivapalan, M., Troy, T. J., van Dijk, A. I. J. M., Van Emmerik, T., Van Huijgevoort, M. H. J., Van Lanen, H. A. J., Vörösmarty, C. J., Wanders, N., Wheater, H. Human-water interface in hydrological modeling: current status and future directions. Hydrol Earth Syst Sc, 21: 4169-4193, doi: 10.5194/hess-21-4169-2017, 2017

Wagener, T., Wheater, H.S. & Gupta, H.V. Rainfall-Runoff Modelling in Gauged and Ungauged Catchments. Imperial College Press, London p. 300, 2004

Wanders, N., van Huijgevoort, M., van Lanen, H., Wada, Y. Natural and human-influenced hydrological simulations for California, https://doi.org/hdl:10411/GP5PKK, DataverseNL Dataverse, V1, 2017

Wilhite, D. A. & Glantz, M. H. Understanding the drought phenomenon: the role of definitions, Water Int. 10(3): 111-120, 1985

Yevjevich, V. An objective approach to definition and investigations of continental hydrologic droughts. Hydrology Papers 23, Colorado State University, Fort Collins, USA, 1967

Zégre, N., Skaugset, A. E., Som, N. A., McDonnell, J. J., Ganio, L. M. In lieu of the paired catchment approach: Hydrologic model change detection at the catchment scale. Water Resour Res, 46(11), doi: 10.1029/2009WR008601, 2010

Table 1: Important catchment characteristics for paired catchment selection.

Catchment characteristic	**Assessment for similarity**
Precipitation	Annual averages (±10%), annual totals, monthly totals, monthly distribution
Potential evapotranspiration	Annual averages (±10%)
Geology and soils	Classifications/typology (similar response)

5

Table 2: Catchment data about each paired catchment case study.

Case study	Human activity	Catchment status	River/ Station	Catchment area (km^2)	Geology	Average annual precipitation (mm)	Average annual flow (mm)	BFI
UK	Ground water abstraction for public water supply and agriculture	Natural	Dun (39028 Hungerford station)	101.3	Mainly chalk based (some clay-with-flints)	829	218	0.95
		Human	Kennet (39037 Malborough station)	142	Chalk dominated (some clay-with-flints)	838	196	0.94
Australia	Ground water abstraction for irrigation	Natural	Cockburn (Mulla Xing station)	907	alluvial overlying fractured rock (granite and sedimentary)	665	64	0.24
		Human	Cox (Tambar Springs station)	1450	bedrock-contained alluvial valley	732	21	0.21

Table 3: Paired catchment analysis results for UK, Kennet (Human) and Dun (Natural).

	Occurrence		**Duration**		**Deficit**		
	Frequency	Total no. of months in drought	Average duration (months)	Maximum duration (months)	Total deficit (mm)	Average deficit (mm)	Maximum deficit (mm)
Natural	15	93	5.8	13	224.3	12	47.6
Human	31	243	7.8	30	1210.9	39.1	186.2
% increase due to the human influence	+107%	+161%	+35%	+131%	+440%	+179%	+291%

5

Table 4: Paired catchment results Australia, Cox (Human) and Cockburn (Natural).

	Occurrence		**Duration**		**Deficit**		
	Frequency	Total no. of months in drought	Average duration (months)	Maximum duration (months)	Total deficit (mm)	Average deficit (mm)	Maximum deficit (mm)
Natural	14	52	3.7	10	14.3	1.0	3.4
Human	39	165	4.2	10	47.3	1.2	3.3
% increase due to the human influence	+179%	+217%	+14%	0%	+231%	+19%	-3%

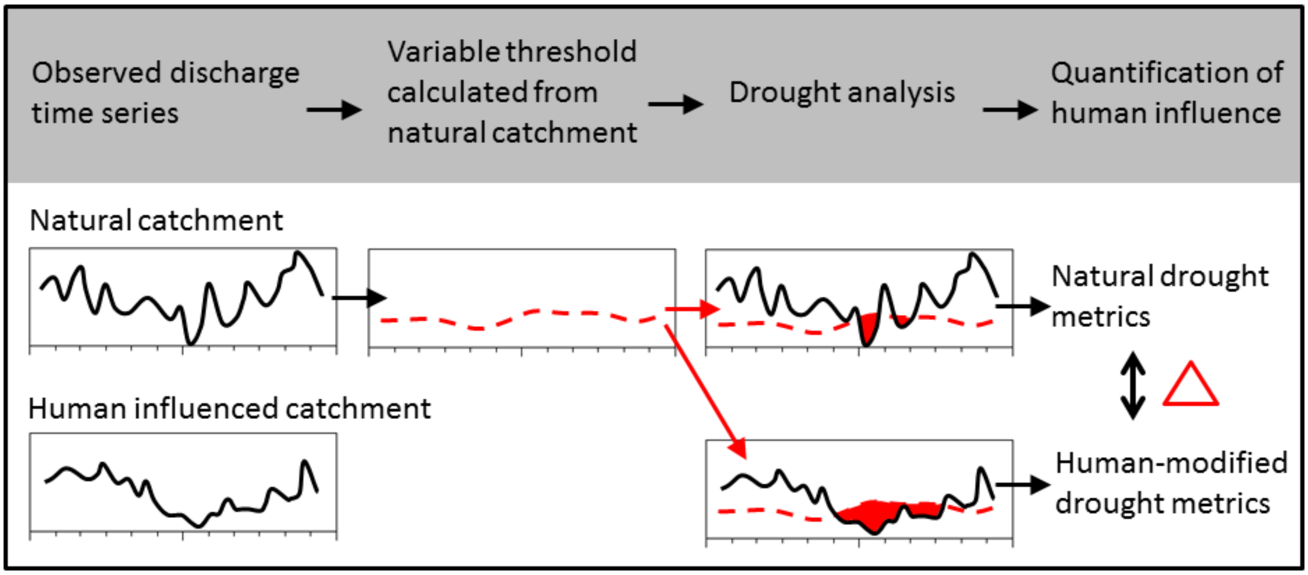

Figure 1: Diagram of the drought analysis method and quantification of the human influence on the hydrological drought metrics.

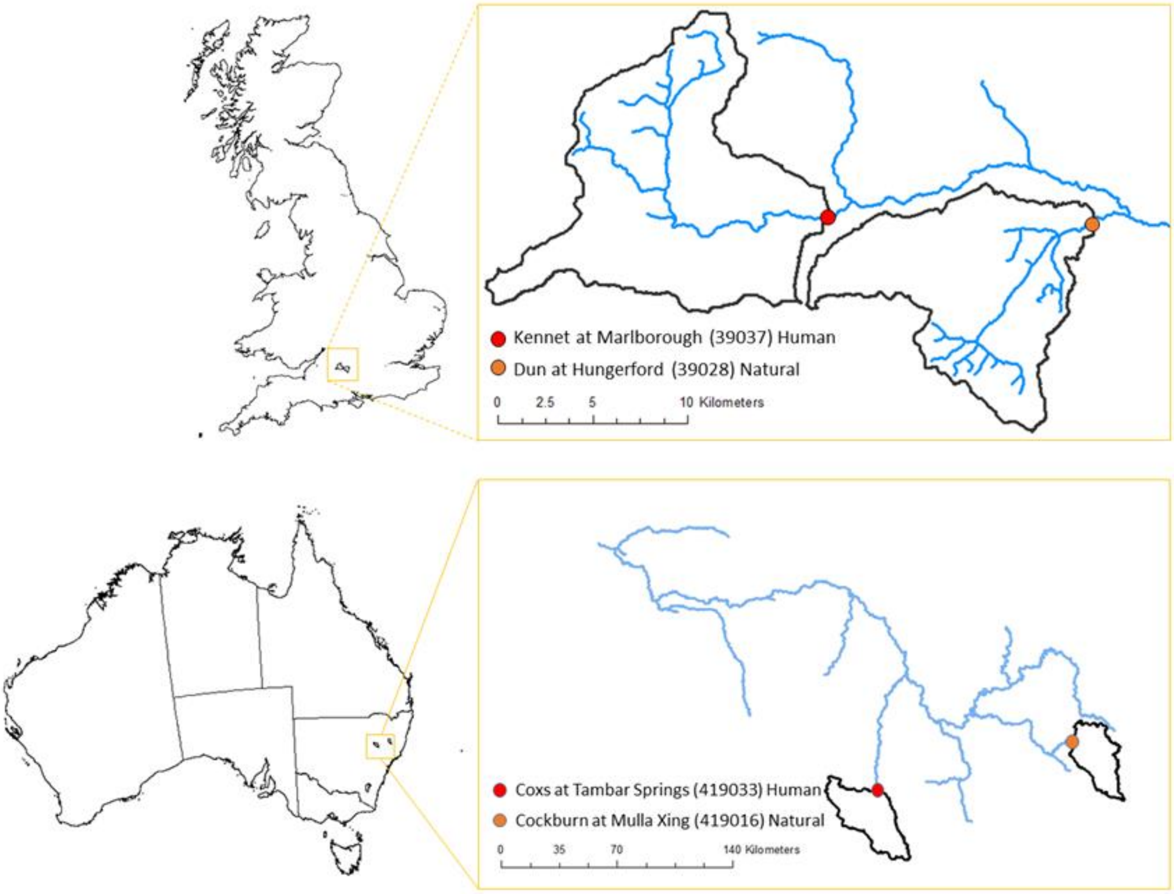

Figure 2: Paired catchment case studies in the UK (top) and Australia (bottom).

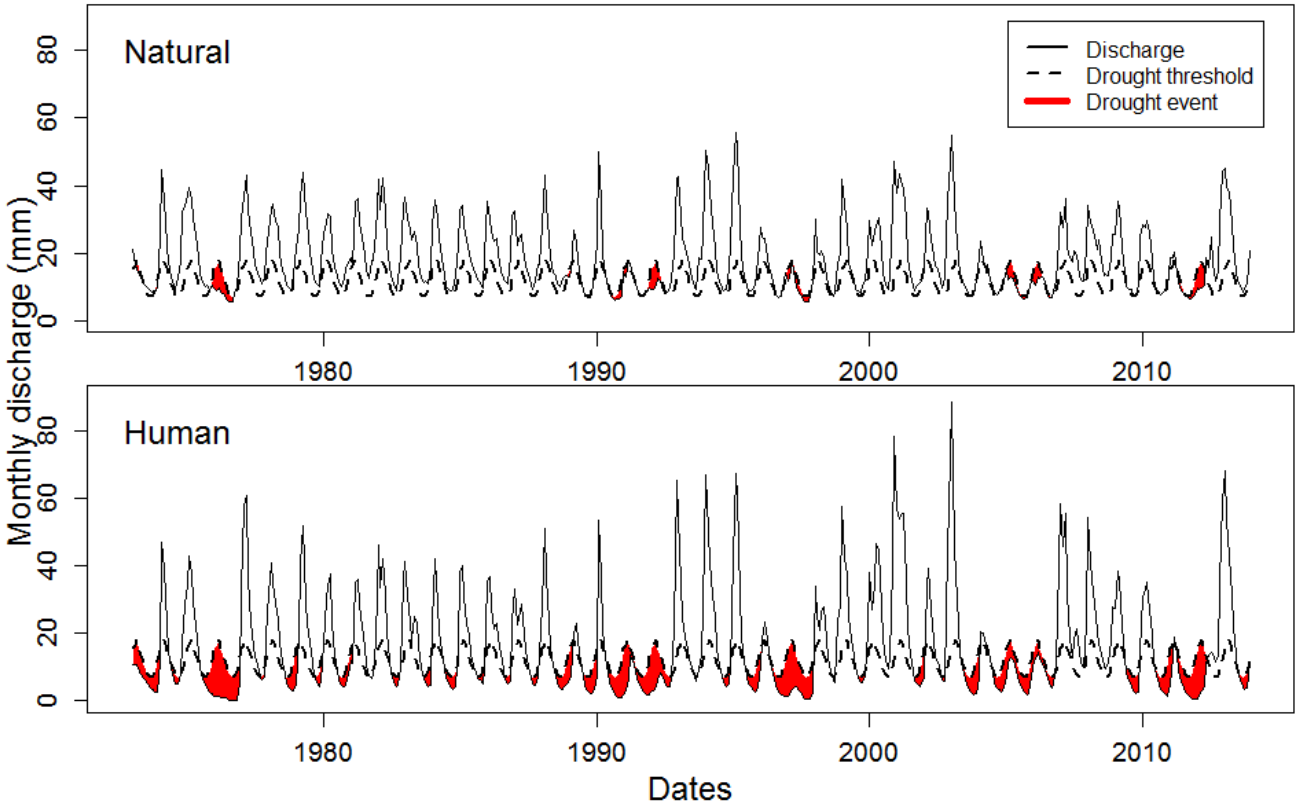

Figure 3: Drought analysis results for the UK pair, Kennet (human) and Dun (natural) (1973 – 2013). Black solid line represents streamflow, dashed black line represents 80% variable threshold, and red areas identified drought events.

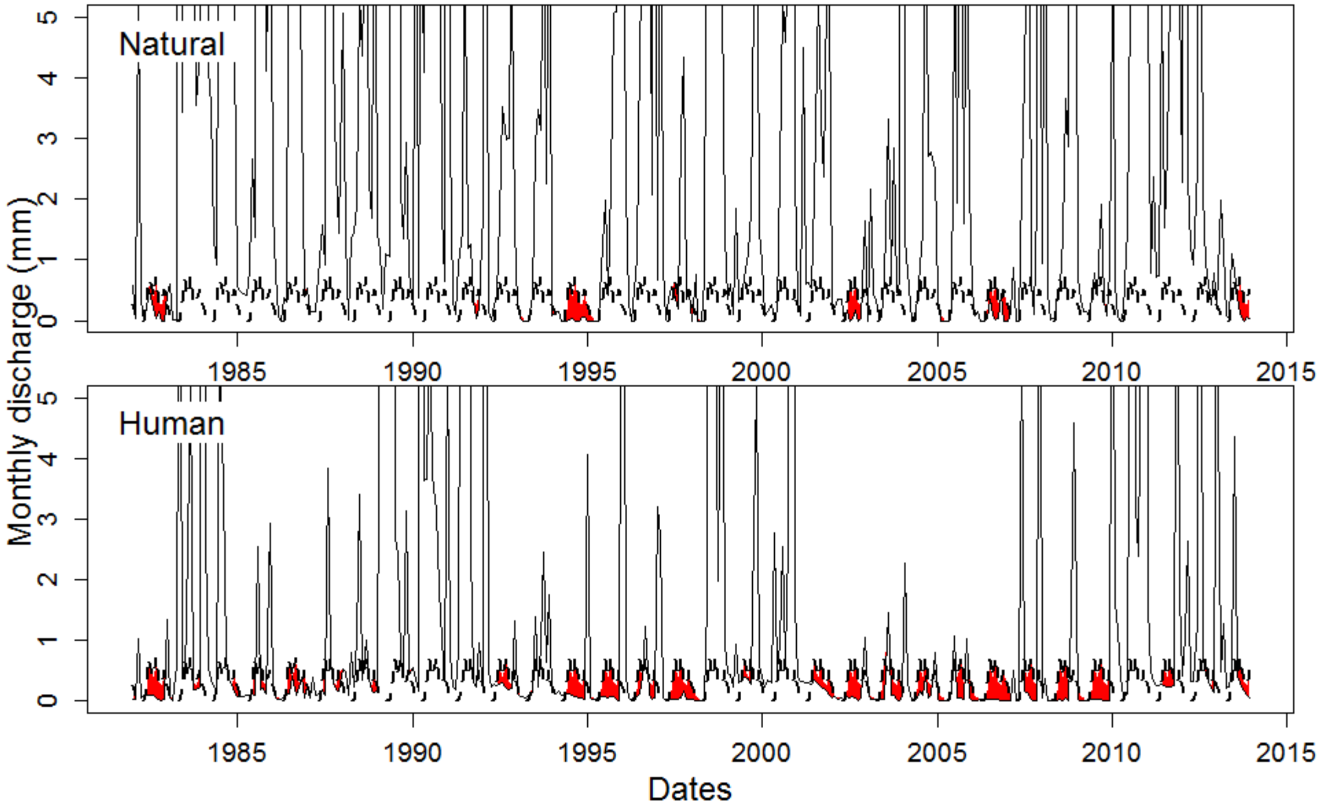

Figure 4: Drought analysis for the Australian pair, Cox (Human) and Cockburn (Natural) (1982 – 2013). Flow higher than 5 mm/month is not shown. Black solid line represents streamflow, dashed black line represents 80% variable threshold, and red areas identified drought events.

5