Editor

Dear authors,

As you have seen, the two reviewers provided detailed comments on your manuscript. They highly appreciate the general research idea and direction. I fully agree with them.

However, they both also highlight the critical need for an in-depth reflection on the choice of catchments for the paired analysis. Considerable doubts are expressed that adequate reference conditions could be established and that the selected catchments do not exhibit sufficient similarity to allow a meaningful analysis. I strongly encourage the authors to address these issues in detail together with the other comments made by the reviewers. I am looking forward to receiving a revised version of your manuscript

Best regards,

Markus Hrachowitz

>> Dear editor, thanks very much for your positive evaluation of our research idea and manuscript. We have taken on board the comments of both reviewers and S Mylevaganam.

In summary we have changed the terminology of the paper (instead of 'natural' we now use the word 'benchmark' catchment) to reflect the fact that we do not require an undisturbed catchment to compare with the human-influenced one in order to quantify the effect of the human activity we are interested in. We also think that this change of terminology from 'natural' catchment to 'benchmark' helps to show the wider applicability of this approach in the Anthropocene. The most significant change to the paper is that we have changed the UK catchment pair, because we felt that it was too contentious to be used as a neutral example case study with the aim to show a methodology. We now show the application of the paired catchment analysis on different human activities with a case study in which human activities alleviate droughts (UK Blackwater) as well as the existing Australian case study, which shows an aggravation of droughts due to the human activity. We believe that this change strengthens the paper and alleviates the reviewers' comments. We have also introduced a flow diagram (Fig.1 to replace the previous Table 1) to illustrate more clearly the selection of paired catchments. Finally, we have improved the general structure and writing of the manuscript following the reviewers' suggestions and our own thorough re-reading of the manuscript and have re-written the abstract so that it matches again the revised manuscript.

Please see below for our response to the reviewers' comments which are given in italics and blue. The page and line numbers mentioned refer to the tracked-changed version of the revised manuscript. We also submit a cleaned version for easier reading of the revised manuscript.

Reviewer #1

>> We thank you for your review and constructive comments. We hope that you find our responses satisfactory to the points that you make.

1a) If the authors are trying to determine the presence of human influences on hydrological drought, they should know the natural or reference influence to drought, i.e., the base hydroclimatic and basin characteristics. The authors do a rigorous hydroclimatic analysis in the way that their "paired" basins are same in size, close to each other, have same PET values, same P values. They have no similar geological characteristics but the authors are aware of this.

However, even though as the authors suggest, finding completely natural basins is difficult, their "isolation of the human influence" is coarse and undocumented, without properly accounting for differences of land use and water use between basins and without considering all the land use and water use already existing in the "natural" catchments.

Groundwater abstraction is not the only human effect that can influence drought characteristics. Just by looking in google earth at the Dun River upstream of Hungeford, UK, I see a basin that is completely agricultural, with barely any patch of natural vegetation. Since land cover/use is a control of water partitioning and runoff (Sterling et al., 2013), I don't know how "natural" is this basin. Additionally, by a quick search in google earth, I see that the river is also completely regulated by embankments and check dams/levies from beginning to end. Since flow regulation alters the partitioning of water and hence runoff (Jaramillo and Destouni, 2015), your reference conditions in terms of intra-annual variability and quantity of flow are already altered by regulation.

This means that your natural catchments are already affected and not eligible for a paired analysis for the purpose you need them. I would look harder for other basins with no water use/regulation and more pristine land covers to represent the "natural" condition, in the UK or abroad. Articles such as (Dynesius and Nilsson, 1994; Jaramillo and Destouni, 2015; Lehner et al., 2011; Nilsson et al., 2005) could help. The Authors can also choose instead of a "paired" analysis of catchments a paired analysis of two groups of catchments, this would make the analysis more robust.

>> The reviewer makes an important comment about classifying the natural catchments as fully natural, and it has made us to reconsider the terminology used in our work to help represent this better. Whilst we fully agree with the reviewers comment that finding a pristine catchment is crucial if one aims to quantify the OVERALL effect of all human influences on drought. However, if we want to use the approach to increase our understanding of how different human activities influence drought we need to be able to isolate a specific type of human influence. Therefore, when comparing a human-influenced catchment with a completely natural catchment, the combined effect of a mix of human activities will be found, which makes it harder to attribute the difference to one type of human influence. It would be extremely difficult to find completely natural catchments that are similar enough to the influenced catchments with only one type of human influence as the difference between them. There are hardly any truly pristine catchments in the UK and most other regions across the world, where there is no water use/regulation and pristine land cover. Any pristine catchments are likely to be incomparable with the 'human' catchments because of their different geology and climate and the human-influenced catchment is likely to have a mix of land-use change, abstraction, etc. To address this, we changed the terminology from 'natural' catchment to 'benchmark' catchment throughout the manuscript and explained more clearly the aim of the approach.

With regard to the choice of the UK catchments – The Dun is one of the UK benchmark catchments (Harrigan et al., 2018), therefore it is considered as a 'natural' catchment by the Centre for Hydrology and Ecology and we are confident in using it as a comparison pair. However, we agree that the choice of UK catchment is too contentious to be used as an example, and we have changed the UK example case study pair to accommodate all reviewers' comments. As UK case study, we now present the pairing of the human-influenced Blackwater catchment and the Chelmer (benchmark catchment), both in South-East England. The Blackwater catchment has a water transfer scheme delivering excess water to the Essex area, helping to keep it wet during the summer in dry years (Robinson, 2011). Tijdeman et al. (2018) suggest pairing with a similar catchment, Chelmer, to *represent the natural situation with very similar catchment characteristics. Chelmer is identified to have minor artificial influences, with the main difference being the water transfer present in Blackwater (see Section 3.1 in the revised manuscript).*

With regard to the choice of Australian catchments – we find that the land use in both catchments is similar (see new Figure 3 with a map of catchment's land use). Both catchments have a mix of natural savannahs and grassland used for grazing, with some dryland cropping. According to Green et al. (2011) the Cox catchment land use is "a combination of grazing and dryland cropping with agriculture". The benchmark catchment, Cockburn, is described as "the area is mainly used for grazing with some dryland cropping and horticulture" (Green et al., 2011). The only difference between the catchments is the heavy groundwater abstraction in the Cox (Ivkovic et al., 2014), which is the human influence we are aiming to quantify (see Section 3.2 in the revised manuscript).

We have added some of these details about the catchments, their land uses and similarities into the revised paper to show this clearly, especially the change of terminology from 'natural' catchment to 'benchmark' catchment.

1b) Furthermore, the authors say that one of the basins suffers from groundwater abstractions while the other one doesn't, at least, for the UK pair. There is no quantification of this, how much, where, since when ground water abstraction in the human affected basin? Any evidence that in the other basin there is no groundwater abstraction, are you sure of this?

The authors should check this for the Australian case too.

>> Unfortunately, we do not have long time series data of actual groundwater abstraction. This is precisely the reason why we are suggesting a paired-catchment approach instead of for example detailed physically-based modelling incorporating detailed data on human activities. Data on human influences in a catchment is generally not available and if it is, it often cannot be shared because it is protected by privacy laws. Of course, qualitative information on the human influence is, however, essential for a successful pairing and attribution of the differences. We have added this to the new Figure 1 and expanded Section 3.1 and 3.2 (of the revised manuscript) to include this qualitative information for our case studies. We changed the UK case study, which now focuses on the effects of water transfer instead of groundwater abstraction. For this water transfer, we have qualitative information about the starting year and purpose of the scheme from AEDA (1990). For Australia, the human-influenced catchment, Cox, is subject to heavy groundwater abstractions (Ivkovic et al., 2014). Although we do not have time series of abstraction, we do know that ACTUAL annual aquifer abstraction rates of the Cox are 11245 ML/yr (Barrett, 2012), whereas LICENCED annual aquifer abstraction licenses for Cockburn are 4481 ML/yr (O'Rourke, 2010). Annual abstractions in the Cox catchment are therefore at least 2.5 times as much as in the Cockburn, but because O'Rourke (2010) reports entitlements only and for the bigger catchment in which the Cockburn is located only 20% of the entitlements is used (O'Rourke, 2010), our estimate is that the actual annual groundwater abstraction in the Cockburn is around 900 ML/yr. The Cox groundwater abstraction would then be more than 12 times as much as the Cockburn.

2) Include some statistics of land use and water use in the Description of the area. Also, improve Figure 2, to show more information on each catchment.

>> We have now provided more information about land use in both paired catchments in the text (see new Section 3.1 and 3.2) and changed Figure 3 to visualise land use information for all catchments. We have also added land use as a selection criterion to Figure 1 and the text in Section 2.1 to show that it is a consideration for catchment selection.

3. The authors should put some statistical significance tests to support further their results.

>> Whilst this would be a useful suggestion, unfortunately there are not enough data points in our analysis for statistical significance tests. We believe that quantifying the percentage change due to the human influence for the overall drought characteristics and showing the basic descriptive statistics of average, maximum and total duration and deficit volumes already provides very relevant information. We considered doing an event-by-event based analysis, but that proved to be impossible, partly because the input data is not completely similar for both catchments leading to small variations between events. Thus, taking a more holistic look at the average, maximum and total drought duration and deficit over the entire time series is the most robust, and scientifically acceptable, information that we can provide. To perform statistical significance tests we would need more (replicate) catchment pairs, which is beyond the scope of this paper but could be an interesting follow-up.

So I like the idea, but a more thorough selection of catchments including land and water use conditions needs to be included in the study

>> Thanks for your summary of the review. We hope that we sufficiently addressed this under items 1 and 2. We believe that adding this information will help to provide the right level of detail for the reader, and the change of terminology from 'natural' catchment to 'benchmark' catchment will help to show how we are aiming to isolate human influence to be able to attribute differences to different types of human activities.

Authors reply to Reviewer 2's comments

Please find our responses and actions to your comments below. Frequently we have placed a number of comments under the same section if they are related and our response covers them jointly. Figures and tables shown here only in this reply have the prefix R (e.g. Figure R1) to distinguish them from those shown in the manuscript. In our response to Reviewer 1, we have suggested that we rename the 'natural' catchment to be termed the 'benchmark' catchment; therefore, the new term is used throughout in our response here.

There are a few major things that we changed in the manuscript in general, which we would like to highlight here before discussing the specific comments. We bullet point these major changes here, which all relate to the framing of the paper and the content:

- *<u>Methodological framework flow diagram.</u> As this is a methods paper, we focus on the methodology aspects and not the results of the case studies. We have introduced a flow diagram to illustrate more clearly the selection of paired catchments.*
- *<u>Demonstrating the method with case studies of different human activities, which alleviate and aggravate droughts.</u> We now show the application of the paired catchment analysis on different human activities with a case study in which human activities alleviate droughts (UK Blackwater) as well as the existing Australian case study, which shows an aggravation of droughts due to the human activity. This changing of the UK paired catchment case study from the Kennet to the new case study of Blackwater addresses a number of Reviewer 2's concerns about the UK pairing.*

Reviewer's comments

This is a generally well written paper on an important topic and the paper has significant potential to make a very worthwhile contribution to the 'drought in the Anthropocene' debate. It is potentially a very useful advance arising from a simple yet potentially very effective idea.

>> We thank you for their overall view of the importance of the topic and paper.

1) Major Reviewer's comment: pairing of UK catchment

Major Comment: impact of catchment (dis)similarity on the proposed method. The method is predicated on the similarity of the donor natural catchment/target influenced catchment, but in the UK example at least, the catchments are not similar enough, very likely leading to over-estimation of the anthropogenic effect.

Catchments are different in terms of runoff response/catchment function, despite their similar rainfall.

Given the more limited range of the Dun flows, my guess is the Q80 of the Dun will be somewhat higher, leading to inflated values for the deviations that are used to infer aggravated drought due to human effects.

>> We realise that a large proportion of the Reviewer 2's comments are addressing the pairing of the UK case study specifically, highlighting the issue of the (dis)similarity between the UK pair and the contentious nature of this catchment. The reviewer's comments help to show the level of information needed for the proposed paired-catchment method, and the importance of a suitable pairing. We have taken on board some of the reviewer's comments to help improve the pairing.

As this is a methods paper and the case studies shown purely demonstrate the method, we found a UK pair that is more similar, as demonstrated by other studies (e.g. Tijdeman et al., 2018), and less contentious, and which helps to demonstrate the use of the paired catchment analysis on a different human activity. Therefore, we have changed our UK case study from the Kennet to the Blackwater catchment (Figure R1). The Blackwater catchment has a water transfer scheme delivering excess water to the Essex area, helping to keep it wet during the summer in dry years (Robinson, 2011). Tijdeman et al. (2018) suggest the pairing with a similar catchment, Chelmer, to represent the natural situation with very similar catchment characteristics. Chelmer is identified to have no artificial water input, with the main difference between the catchments the water transfer present in Blackwater.

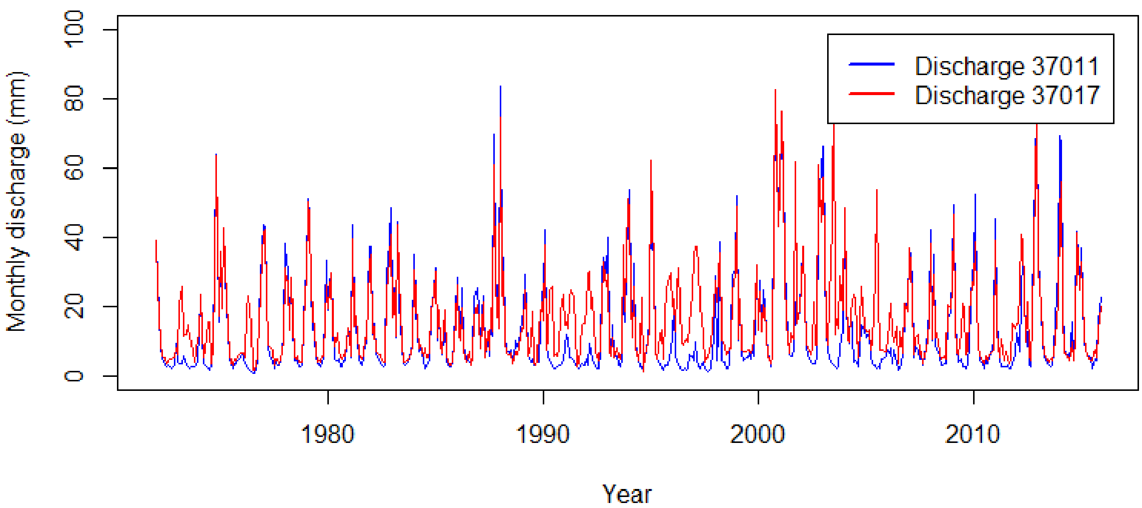

Figure R1: *Discharge plotted (mm/month) for both catchments in new UK case study pair: Benchmark, Chelmer (blue) and human-influenced, Blackwater (red)*

While the focus of this methods paper is to use the case studies to illustrate the method rather than attributing differences to specific causes, we think that choosing a different and less controversial pairing with more similar runoff response will better highlight the advantages of the method.

Please find the rewritten section of the new UK pair in Section 3.1 of the revised paper and updated Table 1, and the new case study results in Table 2 and Figure 3. By changing the UK case study, we hope to have answered the reviewer's questions.

In terms of the results, the figures quoted in Table 3 seem very large. Given the nature of the debate around abstraction impacts, these figures could be quite contentious, as the Kennet is something of a poster child in the debate around sustainable abstraction, and the authors should do more to ensure they are meaningful.

>> We agree that the numbers were very large for our Kennet case study, but this might be realistic given the published concern over over-abstraction in the Kennet area, and recent changes to abstraction rates to reduce this (2014 EA issued a notice reducing the permitted abstraction from Axford and revoked the abstraction licence on the little River Og). Therefore it is legitimate that impacts seen over the previous decades could reflect this over-abstraction.

e.g. "Thames Water accused over dry River Kennet in Wiltshire", BBC, 27 September 2011 (https://www.bbc.co.uk/news/uk-england-wiltshire-15076406)

e.g.2: "For over 20 years there has been local concern that flows in the Upper Kennet above Marlborough have been affected by over-abstraction' (Kennet catchment partnership). (http://www.kennetcatchment.org/issues/over-abstraction/)

However, given that the focus of this paper is to introduce the method, we have changed the UK case study to alleviate this comment (see above).

2) Overall reviewer's comments: considering other approaches to bolster the method / convincingly demonstrate the method:

Given these concerns, the authors could consider some approaches to bolster the method and provide verification – e.g., how this method performs relative to other approaches or modifications, e.g. detecting deviations based on rainfall (as in Tijdeman et al. 2018) and PE.

Paired catchment analysis is a staple of experimental hydrology, but is much harder to do in 'real world' examples when it is not possible to control all variables except the main intervention of interest, and even the latter may be poorly understood.

I feel major revisions are needed to convincingly demonstrate the method, through modifiying it to allow some tolerance in the donor/target relationship, verifying the methods using independent abstraction data, or benchmarking it against other methods.

>> We argue that the paired catchment approach can be extremely beneficial if you have the right level of information to justify the pairing, but not enough detailed data on the human influences themselves (i.e. time series of abstraction rates) or to run alternative approaches. Therefore, the paired catchment approach can help provide insight into the human influence in the catchment from the observation data available and might be a first step to obtain more data to apply alternative

approaches. Exploring the use of other methods to obtain more robust results for the example case studies is not the purpose of the paper. In the revised manuscript, we explain that this method can be complementary to others (see p.2 l.20, p.4 l.14-15 and p.15 l.6-7).

Furthermore, we have also changed the framing of the paper in terms of the case studies presented. We now show a case study which has a human activity aggravating hydrological droughts (e.g. Australia Cox – groundwater abstractions) but also a case study in which the human activity alleviates hydrological droughts (e.g. UK Blackwater – water transfer). We believe that this helps to demonstrate the method and its applicability better.

To help illustrate the method further, we have also added a flow diagram for the pairing of catchments for the analysis, Figure 1.

In general the approach could be strengthened considerably by taking a more water balance approach as done in the classic paired experimental catchment studies, and also in the study of Prosodcimi which incorporates climate variables to account for any confounding effects.

>> In the new framing we have emphasised the use of the paired catchment approach when less detailed information is available to still make an assessment of the difference between the two catchments (p.2 l.1-2, p.3 l.18-19). The use of the same time period as a comparison between the two catchments means that overall climate is accounted for in the analysis, which is an advantage compared to methods comparing data pre- and post-disturbance.

The water balance approach is useful, but does not focus on drought specifically and requires data that is not available; instead we are looking for a method which can be applied to multiple case studies to give an idea about the impact of human activity on drought only based on commonly available data (precipitation and discharge).

3) Reviewers comment: include abstraction rates information

verifying the method using independent abstraction data, or benchmarking it against other methods.

The Kennett is very well known to experience major abstractions, which have been non-stationary over the series. But more could be done to follow this study up – there is anecdotal information on abstractions in various grey literature sources I found online (below).

>> As mentioned, some average annual abstraction values are available for the case studies through grey literature. However, it is difficult to obtain actual abstraction, rather than licenced values and long time series of actual abstraction are impossible to obtain. The paired catchment method is therefore valuable when other methods cannot be applied because quantitative abstraction information is not available. We do agree that qualitative information is needed for the selection of a suitable pair and to interpret results (see new Figure 1). We have therefore added more information to the manuscript (see Section 3.1 and 3.2), also in response to the comments of Reviewer 1 (1-2).

4) Reviewers comment: Impacts and abstraction data

Finally, to really demonstrate the success of the method, it would be nice to have some independent verification of the suggested impacts. I appreciate access to abstraction data is not straightforward for the UK, but might be possible for one catchment, at least for derived data on impacts rather than particular abstractions.

>> We would like to be careful not to allocate too much of the paper to the two case studies as we feel that this will detract away from the focus of the paper, which is the method itself. However, we have included more information here to give a background on the new UK pairing (see new Section 3.1). It is also important to note that gaining the level of information we have for the UK is possible, but it is difficult to get similar data for many other regions of the world, including Australia.

I would suggest some dialogue with the EA would be worthwhile, as there seem to be naturalised data (be decomposition and/or modelling) available for the Kennet for various part studies.

>> We fully agree that a comparison with other methods that rely on modelling is interesting. However, we do not feel that the EA naturalised data can be used as a benchmark or independent verification to compare the paired-catchment results against. Modelling has large uncertainties and especially for the EA naturalisation it is not clear which processes and activities are included in the analysis. Additionally, naturalised data is not available for the Australian catchments.

5) Reviewers comment: using threshold from benchmark catchment

However, transferring a threshold directly from one catchment (reading off the Q80 flow value from the natural catchment and applying it to the influenced one) to another seems like a potentially dangerous business. This might not be a problem if one is just trying to estimate flows at an ungauged site, and can report uncertainties; but in the present method any biases arising from the data transfer could be very misleading.

>> The transferring of thresholds from the donor catchment to the influenced catchment is a basic principle of this application of the paired-catchment approach. Furthermore, the transferring of thresholds from a benchmark situation to a human-influenced situation has been used in other existing literature, with regards to the comparison of naturalised data and observed flow (observation-modelling framework, Van Loon & Van Lanen, 2013; Van Loon & Van Lanen, 2015). It is also used by the large-scale hydrological modelling community when analysing future droughts – use of pristine threshold for both the pristine and human scenarios to calculate the modelled human impact on hydrological droughts (e.g. Wanders & Wada, 2015).

The main issue with using a threshold established on the human-influenced catchment discharge is that the effect of the human activities is then included in the threshold used to calculate droughts. We feel that this is even more misleading as it underestimates the effect of the human influence. For a fair quantification of the effect of human influence on drought we therefore adhere to using the same point of reference (the same threshold) for both catchments.

6) Reviewers comment: Impact of catchment (dis)similarity on the proposed method

Put simply, the method applied in this paper can only work if the donor's natural flow regimes is near-identical to the 'theoretical natural' flow regime of the target site. Any deviation between these regimes will be interpreted as anthropogenic; when it could just be due to the variations between two catchments that appear quite similar but are in fact different.

It is difficult to find suitable pairs. Even when catchments are in principle very similar (geology, rainfall etc), the concept of 'uniqueness of place' is a major obstacle.

>> We agree that 100% proof of similarity cannot be given. Experimental hydrology (control and treated catchments/plots) and models are also unable to provide this. We can only reliably check the similarity of both catchments if we have long time series (preferably 30 years) for the donor and the human-influenced catchment prior to human disturbance. In practice, this will be very rare or non-

existing for catchment pairs. We now mention this aspect more clearly in the revised manuscript (e.g. p.1 l.17, p.6 l.18-23, p.14 l.18-26).

As a result, I do not think the authors can claim 'attribution', and the claims of the paper need to be reconsidered.

Note that this an important difference in the urbanisation paper (Prosdocimi et al., 2015) or in the classic experimental catchments, which all incorporate some data on the intervention in question into the analysis (e.g. the land cover data used by Prosdocimi et al.).

>> We agree and we have rephrased our results from attribution to explanation or isolation throughout the manuscript. We have also covered this topic in our revised Discussion section (p.15 l.3-7) and Conclusion (p.15 l.32).

Specific reviewer's comments

A technical matter: In Figure 3, I'm surprised to see so little of the flows being below the threshold. It does not look like 20% of the flows are below the threshold to me – can the authors please check?

>> We can confirm that it is correct. The total number of months in drought (Table 3) is close to 20%: 93 months in drought out of 540 months (17%). It is not the full 20% because we have dropped minor droughts that were only 1 month in duration.

P2, L21. Another approach is using deviations in the P-Q relationship, e.g. Tijdeman et al., 2018.

>> This has been added in (p.3 l.33 – p.4 l.2).

P2, Intro. The paper would do well to refer to the expansive literature in hydroecology which also tackles a similar problem of estimating 'natural' flows for sites, against which impacted flows can be compared. The classic papers of Brian Richter are a good start, and I'm fairly sure methods have been proposed to transfer natural flow percentiles (but using a whole FDC approach; try the DHRAM work by Andrew Black, Dundee as a start). Another area where this is done routinely is through the LowFlow software produce, a regionalisation product which estimates natural and disturbed FDCs at any site. Its not drought specific, but definitely has a very similar aim.

>> We agree that literature from the hydroecology field should be brought in to show how they address the similar problem. We thank the reviewer for the suggestion and we have updated the Introduction (p.3 l.6-8, p.6 l.20-23) and the Discussion (p.14 l.23-26).

P4, Sect. 2.3 Given the concerns raised about the UK catchments, this section needs to be reconsidered.

>> This section has been changed in the revised manuscript to introduce the new case study, Blackwater, and update all associated sections (Section 3.1), tables (Table 1, 2) and figures (Figure 3, 4).

P6, L2. The 80th percentile is not what is being used here. This paper uses the 20th percentile, or, as is most commonly referred to in hydrology, Q80: the 80% non exceedance threshold from the flow duration curve.

>> The authors agree that this needed rewording, and this has been done in the revised version of the manuscript (p.9 l.17-20).

Discussion: is generally very insightful but definitely needs reconsidering in light of catchment selection issues, and claims about attribution needed to be moderated.

>> We thank the reviewer for their comment and the suggestion to highlight the limitations and issues further. We have changed the discussion to include more about these aspects (see Section 4).

We thank the reviewer for all their comments and suggestions, and we hope that a number of them have been satisfied by the change of UK catchment, and that we have strengthened the paper with the suggestions enhanced analysis and provided a clearer aim (i.e. a methodological paper rather than a case-study type of paper).

Short comment by S Mylevaganam

We thank you for your review and constructive comments. We hope that you find our responses satisfactory to the points that you make.

1) As per the authors, research using the paired catchment approach to assess change in hydrological "droughts" due to land use and other human activities remains limited(see P-3 LN-29). However, as per the authors, research works using the paired catchment approach to assess "low flows" due to land use and other human activities are found in the literature(see P-3 LN-24:29). What are low flows? What are droughts? I think, the distinction between low flows and droughts needs to be explicitly mentioned in the manuscript to assert the authors' statement that the research using the paired catchment approach to assess change in hydrological "droughts" due to land use and other human activities remains limited. Moreover, what is implied by "limited"? Should the authors include/cite the research works using the paired catchment approach to assess change in hydrological "droughts" due to land use and other human activities found in the literature?

>> We thank the reviewer for pointing out this for clarification. In the original manuscript, we defined droughts at the end of the first paragraph (revised manuscript p.2 l.31 – p.3 l.2). However we have now included a definition of low flows (p.5 l.21-22) and added a brief description of how these two terms differ to make it clearer to the reader (p.5 l.28-29).

By "limited" we mean that there are actually no published articles specifically assessing effects of human activities on hydrological droughts using paired catchments. Tijdeman et al. (2018) use the concept of comparing droughts occurring in two similar catchments (e.g. Supplementary figure S4). They do not use a specific framework as we present here, but they explicitly state the potential use for it: "An alternative approach is based on the principles of paired catchment analysis, a concept that has been a foundation of process hydrology. Typically, a paired catchment study compares the flow regimes of nearby catchments with similar physical characteristics. The approach has been applied in numerous iconic experimental studies to investigate land use impacts on river flow (e.g. review of Brown et al., 2005). However, the paired catchment concept can also be used to study human influences on streamflow, using existing gauging station networks, if appropriate "donor" natural catchments with similar flow regimes can be found for "target" catchments with known influences (as conducted in the case of urbanisation effects on floods; Prosdocimi et al., 2015)." (Tijdeman et al., 2018, p.1053). We have changed the statement in the manuscript to demonstrate that there are no published articles specifically assessing human activities on hydrological droughts using paired catchments (p.5 l.29-30).

2) As per the authors, drought analysis is normally conducted on the daily or monthly time step (see P-5 LN-23). Therefore, the authors use "monthly" data for the paired catchment analysis, even

though the selected catchments are provided with data on daily time step? In the current version of the manuscript, the authors fail to state the reason for using "monthly" data for the paired catchment analysis. Is it the methodology (i.e., paired catchment) that is chosen in the proposed approach forces the authors to use the monthly data instead of daily data? Should the authors show the characteristics of the droughts within a month for the selected catchments? What is the minimum duration (in days) of the drought observed in the selected catchments? What is the minimum frequency (in days) of the drought observed in the selected catchments? Would not these details justify the applicability of selecting the monthly time step to conduct the drought analysis?

>> As stated in the manuscript (p.8 l.30 – p.9 l.2), drought analysis is commonly done on the monthly time step, therefore it is deemed justifiable. Droughts are generally long phenomena with timescales of weeks to years, with drought-generating processes and associated impacts going beyond a daily time step.

Furthermore, monthly data was used to avoid a need for pooling of drought events, and to allow minor droughts of <1 month to be dropped. Ultimately as long as the same time resolution and threshold is used for both catchments then the comparison remains valid.

3) The use of paired catchment in the proposed approach is very much subjective. Is it possible to define hydrologically similar catchments without considering the landuse pattern and spatial orientation of the landuse? Would it be possible to completely define hydrologically similar catchments using precipitation, PET, and geology? The landuse pattern than the spatial orientation of the landuse may dramatically alter the flow pattern even for the same precipitation, PET, and geology?

>> We do consider land use (see reply to comment 2 of Reviewer 1) and land use is similar for the catchment pairs. We have now included this catchment characteristic into Figure 1 and 3 to show the importance.

4) In Table 3, for Dun (natural catchment), how did the authors compute the total number of months in drought and the frequency? Since the authors have analyzed from 1973 to 2013, there are 12*41(=492) monthly flow records. In other words, setting 80% as the threshold level yields around 98 months in drought (see Table 3). What is the definition of frequency? Is it meant for the return period of the drought? What is the unit of frequency?

>> Because minor drought events of 1 month have been dropped, it might result in slightly less drought events being identified than expected. However, our previous results show that the Dun has 93 months in drought, which is extremely close to this expected 98 months, and the differences seen between the two numbers is purely because of the dropping of minor drought events.

Frequency = number of drought events identified in the time period. This definition is now included in the revised version of the manuscript (p.9 l.31-32). There is no unit for frequency as it is just a value representing the number of drought events identified.

5) In the current version of the manuscript, the authors evaluate the groundwater abstraction on the droughts. With groundwater abstraction, it is expected to have a depleted groundwater table. Consequently, as per Darcy's law, since one of the drivers (i.e., hydraulic gradient) is changed due to groundwater abstraction, a possible alteration on the base flow (see the reported BFI values in UK) that defines the low flow conditions in most of the rivers is expected. Would it be possible for the authors to show the rainfall pattern (daily) in the natural catchment and human altered catchment for some of the drought periods in UK?

>> Indeed groundwater abstraction leads to lower groundwater heads, decreased groundwater gradients, lower groundwater inflow/base flow into the rivers, and hence more extreme drought in streamflow. It is important to note that we do not take an event-by-event analysis though (as it is a challenge to pair drought events in different catchments), but look at overall averages, maximums and totals of drought duration and deficit over the entire time series to avoid this level of discretion.

6) As per the authors, the paired catchment approach has been a predominant method for detecting the effects of disturbance on catchment scale hydrology (see P-3 LN-14). To support this statement, the authors cite Zégre et al., 2010. Considering the fact that the paired catchment approach has been used for many decades (see P-3 LN-16), starting as early as 1920 (see P-3 LN-19), would it possible for the authors to state the reason for citing Zégre et al., 2010 to support the statement(see P-3 LN-14)

>> Thanks for this comment. In our revised version we have changed this citation to one of an earlier time period, that of Bates (1921), which is the first paired-catchment study (p.4 l.29-30).

7) Should the section 2.1 be re-written? The third paragraph of section 2.1 is about the method (i.e., paired catchment approach). In other words, the third paragraph of section 2.1 defines the method. However, the first and the second paragraphs of section 2.1 briefly summarize the crux of some of the previous research works using the paired catchment approach found in the literature. Does it make sense to mention the previous research works using the paired catchment approach at first and then define the method? From the reader's point of view, the third paragraph of section 2.1 should come first and then the previous research works using the paired catchment approach found in the literature.

>> This restructuring of section 2.1 is done in the revised version (see new Section 1.2).

8) The section that is devoted for discussion (i.e., section 4.0) is structured using some of the limitations of the approach presented in the manuscript. What is expected in the section (i.e., discussion) by a reader of the manuscript is left missing in the current version of the manuscript.

>> We believe that because the aim of the paper is to present the novel application of a simple framework for quantifying the human influence on hydrological droughts, this is the important aspect to be discussed in this section, rather than the results of the two case studies which are used to demonstrate the method. Discussing the limitations and the possible ways forward for future research with this method is useful for future research, given its scalability to be performed in other locations.

9) From the reader' point of view, the numbering of the sections is misleading. In section 2.2, the authors introduce the approach used in the current version of the manuscript to address the intended tasks (i.e., determination of drought metrics). However, in section 2.2, the authors ends the paragraph (see P-4 LN-17: here we outline the important elements for the "approach") to form the subsections that need to be listed under section 2.2. Should the sections 2.3, 2.4, and 2.5 be numbered as section 2.2.1, 2.2.2, and 2.2.3?

>> We agree that the numbering here could be improved. We have made Section 1.2 "Paired-catchment analysis" its own section within the introduction, followed by Section 1.3 "Aim". This enables Section 2 onwards to focus on the specific application of the method and the relevant information for the analysis.

10) On P-3(see LN-22), what is meant by "see review of Brown et al., 2005"? Is it a review about Brown et al., 2015? On P-3(see LN-24), what is meant by "some studies included low flows"?

>> We are referring to the published review of paired catchments written by Brown et al. (2005) titled 'A review of paired catchment studies for determining changes in water yield resulting from alterations in vegetation', however we have changed the phrasing of this to be clearer (p.5 l.17-19).

Most paired catchment studies look at annual changes following treatment, and often focus on water yield and high flows, not on low flows or streamflow during droughts. Therefore we specifically point out that some look at low flows, but not the majority of the published literature. P.5 l.20-30 is an entire paragraph which summarises and points to the work which does use paired catchments to look at low flows.

Minor Comments:

a) The authors' marriage to some of the words (e.g., "here" we suggest, "here" we outline, we "here" give, "here" we use, "here" the 80% percentile, "here" we have analyzed, "here" we present, "here" we have demonstrated, "here" we focused, "here" the focus was, and "here" we show) is a little off from what is expected in a scientific research paper.

>> We have endeavoured to address this repetition throughout the revised version of the manuscript.

b) In Table 1, the title of the second column (i.e., "assessment for similarity") needs to be changed to reflect the cell values.

>> Table 1 has been replaced with a new Figure 1.

c) In Table 2, the widths of the columns (e.g., column-7) need to be adjusted to fit the content.

>> This table has been adjusted to fit the content.

d) In Table 2, the gage numbers for the selected catchments in Australia are missing (see Figure 2 and Table 2).

>> Thank you for pointing this out, these have been added to the revised version.

e) In Figure 3, the label for the x-axis should be "year"?

>> X axis label have been changed to Year rather than Dates in this revised version.

f) In Figure 4, the label for the x-axis should be "year"?

>> X axis label has been changed to Year rather than Dates in this revised version.

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Using paired catchments to quantify the human influence on hydrological droughts

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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.~~ Quantifying the influence of human activities, such as reservoir building, water abstraction, and land use change, on hydrology is crucial for sustainable future water management, especially during drought. Model-based methods are very time-consuming to set up and require a good understanding of human processes and time series of water abstraction, land use change and water infrastructure and management, which often are

not available. Therefore, observation-based methods are being developed that give an indication of the direction and magnitude of the human influence on hydrological drought based on limited data. We suggest adding to those methods a ‘paired-catchment’ approach, based on the classic hydrology approach that was developed in the 1920s for assessing the impact of land cover treatment on water quantity and quality. When applying the paired-catchment approach to long-term pre-existing human influences trying to detect an influence on extreme events such as droughts, a good catchment selection is crucial. The disturbed catchment needs to be paired with a catchment that is similar in all aspects except for the human activity under study, in that way isolating the effect of that specific activity. In this paper, we present a framework for selecting suitable paired catchments for the study of the human influence on hydrological drought. Essential elements in this framework are the availability of qualitative information on the human activities (type, timing and magnitude), and similarity of climate and geology between the catchments. We show the application of the framework on two contrasting case studies, one impacted by groundwater abstraction and one with a water transfer from another region. Applying the paired-catchment approach showed how the groundwater abstraction aggravated streamflow drought by more than 200% for some metrics (total drought duration and total drought deficit) and the water transfer alleviated droughts with 25 to 80%, dependent on the metric. Benefits of the paired-catchment approach are that climate variability between pre- and post-disturbance periods does not have to be considered as the same time periods are used for analysis, and that it avoids assumptions considered when partly or fully relying on simulation modelling. Limitations of the approach are that finding a suitable catchment pair can be very challenging, often no pre-disturbance records are available to establish the natural difference between the catchments, and long time series of hydrological data are needed to robustly detect the effect of the human activities on hydrological drought. We suggest that the approach can be used for a first estimate of the human influence on hydrological drought, to steer campaigns to collect more data, and to complement and improve other existing methods (e.g. model-based approaches).
~~.~~

1 Introduction

1.1 Background

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~~ the management of water resources, ~~but also the representation of human activities in environmental modelling. One area where research has been~~especially during drought. Only limited~~, but has increased in recent years, is~~ studies exist that focus on 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~~). This has inspired 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~~define drought as a deficit in available water from ‘normal’ conditions (Wilhite & Glantz, 1985; Tallaksen & Van Lanen, 2004~~), with a~~) and we focus on hydrological drought, which ~~considers the~~is a deficit in streamflow.

~~Currently, using simulation data from hydrological modelling is one of the main ways in~~ Recent studies quantifying the human influence on hydrological droughts~~,~~ use hydrological models because of ~~its~~their ability to isolate ~~variables and input data~~ processes by generating ~~natural~~scenarios with and without human ~~influenced data~~activities 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). Also in other fields, such as hydroecology, modelling is used to quantify hydrologic alteration, i.e. the deviation of flows between actual and baseline conditions (e.g. Poff et al., 2010; Mathews and Richter, 2007). Often this ~~“~~‘scenario ~~modelling” approach~~modelling’ is done with large-scale models (e.g. Veldkamp et al., 2015; Wada et al., 2017; Wanders et al., 2017), but these models have a coarse resolution and are not extensively calibrated or validated locally, and will therefore have large uncertainty~~.~~ on the local scale. Furthermore, whilst the scientific community is ~~seeking~~working to add known human ~~influences~~activities and decisions into hydrological models (Wada et al., 2017), the current generation of hydrological models ~~do~~does 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~~ Finally, scenario modelling requires high-resolution data on ~~observation data, such as the following three: (1) the observation modelling approach (here called “observed-naturalised”) (e.g.~~ human activities influencing the hydrology of a catchment (e.g. land use, abstraction), which often are not available. Therefore, we need relatively simple methods that can estimate the influence of human activities on drought from observational data. Several methods have been developed in recent years:

(1) the ‘observation-modelling’ approach (e.g. Van Loon & Van Lanen, 2013) ~~uses naturalised simulation data to compare to~~compares human-influenced ~~observation data. However,~~observed droughts with naturalised simulated droughts. Downsides of this method are that the simulated hydrological data ~~also~~ have uncertainties and a pre-disturbed period is needed for calibration to reduce those;

(2) the ~~“~~‘upstream-~~downstream”~~downstream’ approach (Rangecroft et al., 2016) compares hydrological droughts downstream of a disturbance with those upstream, which are assumed to be unaffected. This method uses observation data only and uncertainty ~~stems~~comes from the possible non-linear relationship between the upstream and downstream gauging stations;

(3) ~~Another approach using only observation data is the “~~the ‘pre-post-~~disturbance”~~disturbance’ approach (e.g. Liu et al., 2016~~), however~~) compares hydrological droughts before and after a disturbance. 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~~.~~ (Peñas et al., 2016);

~~Instead~~(4) and finally, the ‘large-scale screening’ approach (e.g. Tijdeman et al., 2018) uses deviations in the relationship of meteorological to hydrological drought between a human-influenced catchment and a range of benchmark catchments.

Downside of this method is the need for a large number of catchments with long time series of hydrological data and information about the type and degree of human influence.

In this paper, we suggest to ~~use~~ add an observation-based approach that requires very little data and uses the same ~~analysed~~time period~~, but employing two different catchments to represent the natural and the human~~ for the analysis, thereby avoiding effects of climatic variability and non-stationarity. The ‘paired-catchment’ approach compares a human-influenced ~~situation, a “paired catchment” approach. An existing classic hydrological approach used to detect changes in catchment hydrology, the paired~~ catchment ~~analysis~~with a benchmark catchment where the human activity of interest is not present. Paired-catchment analysis is a classical method in hydrology that compares the flow regime of two catchments which have similar physical characteristics~~,~~ with the aim to identify the impact of a disturbance on the flow regime (Hewlett, 1971; Bosch & Hewlett, 1982). The approach has been ~~used~~ successfully applied 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~~). There are some paired-catchment studies focusing on low flows, but no applications investigating ~~impacts~~human influence on ~~the~~ hydrological ~~phenomena of~~ drought. We argue that this paired-catchment approach could help quantify the human influence on hydrological 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~~

1.2 Paired-catchment analysis

The paired-catchment approach is a classic method for detecting the effects of disturbance on catchment hydrology (Bates, 1921; Zégre et al., 2010). It originates from experimental research on the effects of intentional land cover treatment (e.g. afforestation, deforestation) on water quantity and quality. The basic concept of the method is to compare the flow regime of two nearby catchments with similar physical characteristics, one as a control (‘benchmark’) and the other as a disturbed catchment (also known as the ‘treatment catchment’ in some of the literature). Comparing the same time periods allows for climatic variability to be accounted for in the analysis (Brown et al., 2005). Climate, soils and geology should be similar between the two catchments (Best et al., 2003; Brown et al., 2005; Folton et al., 2015), with the main difference the treatment in the disturbed catchment. Traditionally, this treatment often consists of deforestation or afforestation. The identified differences in hydrology between the disturbed and control catchments can then be attributed to the treatment (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. Relatively short time periods are used for the analysis of the effects of the treatment, typically a few months to years. For classic paired-catchment treatment studies, pre-disturbance periods are sometimes used for both catchments to ensure streamflow similarity, or to establish the pre-disturbance difference in hydrology between the catchments.

The paired-catchment 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).~~2016). 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 the review paper of paired-catchment analysis by Brown et al., 2005~~;~~; and other studies by Cornish, 1993; Bari et al., 1996; Best et al., 2003; Folton~~ et al., 2015; Prosdocimi~~ et al., 2015).

In the 1990s, some studies ~~included~~started looking at low flows within paired-catchment analysis (e.g. Keppeler & Ziemer, 1990; Scott & Smith, 1997). Low flows are defined as the “minimum flow in a river during the dry periods of the year”, which makes them a seasonal phenomenon and an integral component of the flow regime of a river (Smakhtin, 2001). It has for example 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~~Paired-catchment studies focusing on low ~~flow works~~flows 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~~Droughts differ from low flows because they represent an anomaly from the normal seasonal cycle and can therefore also occur in the high flow season. There currently is no research using the paired-catchment approach to assess ~~change~~changes in hydrological droughts due to land use change 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 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~~ Because droughts are extreme events that occur irregularly, long time series are needed to detect any effect of human influences on hydrological drought using a paired-catchment approach. Additionally, many human activities cannot be applied as intentional treatment in a small catchment just for research purposes. This is the case for example with reservoirs, groundwater abstraction and other large-scale water supply and management activities. If we want to study the effects of these on hydrological drought, we need to work with existing observed data. Often no hydrological monitoring was done before the start of the human activity, which means that pre-disturbance data is not available to assess catchment similarity. Despite this, the paired-catchment approach can still be used if the selection of the catchment pair is done carefully and qualitative data on the human activities is available. In hydroecology, a similar approach (termed ‘control-impact’) has been found to give satisfactory results for a range of hydrological variables compared to a baseline approach that used paired catchments that were calibrated on a pre-disturbance period (Peñas et al., 2016). Such a long-term paired-catchment study has recently been done to assess the influence of urbanisation on flooding in the UK (Prosdocimi et al., 2015) and we think that there is potential also to use the paired-catchment approach in drought studies.

1.3 Aim

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 examples of how this approach can help to generate knowledge on the human influence on hydrological droughts from observation data at the catchment scale. The two contrasting case studies used here have water added (via water transfer) or removed (via groundwater abstraction) in the human-influenced catchment. By showing the application of the paired-catchment approach to drought and discussing its limitations, we demonstrate how this approach can be used as tool for improved analysis and understanding of the human influence on hydrological drought in the Anthropocene.

2. Application of the paired-catchment approach to quantify the human influence on ~~droughts. In this context, an undisturbed (natural) and a disturbed (human~~ hydrological drought

For applying the paired-catchment approach to quantify the human influence on hydrological drought, two catchments need to be selected, of which one is a human-influenced~~, ~~ catchment (e.g. with water abstraction, urbanisation, reservoirs) ~~catchment are used,~~ and the other is as similar as possible except that it does not have the human influence we aim to quantify. Importantly, the benchmark catchment does not need to be completely natural to be used in a paired-catchment setting as long as the human influence of interest can be isolated and quantified. The analysis focuses on the effect on hydrological drought metrics (e.g. drought ~~durations~~duration and deficit ~~volumes~~volume), rather than the more typical focus of paired-catchment studies on water yield or low flows~~ in general. Here~~. Therefore, long time series are needed to extract these drought metrics. In this section, we outline the important elements for the approach, such as the ~~characteristics involved in the~~ catchment selection process, the data ~~required~~requirements, the drought analysis, and the calculation for quantifying the human influence.

2.~~3~~1 Catchment selection

The starting point for a paired-catchment analysis is a human activity that is expected to influence the hydrology of an area. Qualitative information about this human influence (such as type and timing) and long time series of hydrological data need to be available (Fig. 1). 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~~that is being ~~quantified~~analysed. Relevant catchment characteristics could include precipitation, temperature ~~(~~or potential evapotranspiration~~)~~, land use, catchment area, elevation, geology, and 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.~~which makes it difficult to automatise the process. Paired catchments are therefore often chosen manually using expert judgement.

In Fig. 1, we provide some guidance on which characteristics are important for this application of the paired-catchment approach to drought, and how these could be assessed. For drought studies, precipitation, potential evapotranspiration ~~(PET)~~, soils~~ and~~, geology and land use 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~~geological classification~~/typology (see Table~~ (Fig. 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~~distribution between the catchments significantly diverted from the 1:1-line or had linear regression slopes and R^2 values of less than 0.5 were excluded from the paired-catchment analysis. ~~Geology/soils have~~Soil type and geology are important to ~~be checked on~~ consider with regard to their responsiveness, i.e. flashy versus slow response to precipitation, implying that ~~the geology and soils need to be translated based on~~ expert knowledge~~.~~ is needed to translate the qualitative soil and geology information. To enable ~~the attribution of change to~~ isolating the ~~known~~ effect of the human ~~influence~~activity on drought, the catchment selection also requires a singular human influence ~~if possible, or dominant human influence~~that is different between the paired catchments.

For our application of the paired-catchment analysis there are some catchment characteristics ~~which are not appropriate for~~that cannot be used as catchment selection criterion. For example, the ~~catchment selection process.~~ Base Flow Index (BFI) calculated from discharge ~~records is not~~data cannot be used ~~as a~~in catchment selection ~~characteristic~~ because the BFI ~~value in a~~of the human-influenced catchment ~~might be~~is probably affected by the human activity. ~~Similarity of BFI values can only be tested if reliable data from a pre-disturbance period is available.~~ The proximity of catchments ~~is also not a set~~a good starting point in the search for similar catchments. However, it may not be a useful catchment selection criterion because neighbouring catchments ~~can actually~~may 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.~~) or because the human influence crosses catchment boundaries (e.g. groundwater abstraction, urbanisation).

2.~~4~~2 Data requirements

Ideally, observation data of precipitation and discharge ~~records for~~with a minimum of 30 years should be used, with limited missing data (< 5%) so that ~~robust statistics can be computed for~~ hydrological extremes can be computed reliably (McKee et al., 1993; Rees et al., 2004). Information on catchment characteristics ~~(in this case annual precipitation and geology) and~~ and the type of human activity in the human-influenced catchment are also required~~.~~

~~Although~~ (Fig. 1). Most commonly, the paired-catchment approach is ~~most commonly used~~done with annual data, ~~it has also been used with~~but monthly data is also sometimes used (Bari et al., 1996; Brown et al., 2005). Droughts are generally long phenomena with timescales of weeks to years, with drought-generating processes and associated impacts going beyond a daily time step. Therefore 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~~). Consequently, here we use monthly data for the paired-catchment analysis.

2.~~5~~3 Drought analysis

~~For each catchment, drought events and their metrics were identified with the commonly used drought analysis method,~~Drought analysis can be done with several different methods (Van Loon, 2015). For paired-catchment analysis we suggest using the threshold level method (Yevjevich, 1967; Tallaksen & Van Lanen, 2004~~; Van Loon, 2015). Drought event~~) to identify drought events and their metrics~~ such as timing (start date, end date), duration (months) and deficit volumes (mm) were extracted from~~, because it allows to use the ~~observation data time series. These metrics were then compared within each paired catchment, allowing the difference due to ~~benchmark regime to compare the human~~ influence to be estimated (Figure 1).~~

-influenced flow against. The threshold level method is a commonly used drought analysis method that defines drought events when ~~data (~~streamflow~~) are~~ is below a specified threshold (Yevjevich, 1967; Hisdal & Tallaksen, 2000; Hisdal et al., 2004; Fleig et al., 2006). ~~Here the 80^{th} percentile was used as~~For quantification of the human influence, the threshold~~, meaning~~ needs to be generated from the benchmark catchment time series (Fig. 2; Van Loon & Van Lanen, 2013), therefore excluding any influence of human activities on the threshold. This benchmark threshold is then applied to both catchments for the drought analysis (Fig. 2).

Different threshold levels can be used. In the case studies described here, we used the 80% non-exceedance threshold (Q80) from the flow duration curve. This means that 80% of the time discharge is above ~~the~~this threshold. The ~~80^{th} percentile~~Q80 is a commonly used threshold to identify drought events (Hisdal & Tallaksen, 2000; Tallaksen and Van Lanen, 2004; Fleig et al., 2006; ~~Van Huijgevoort et al., 2012; Van Loon & Van Lanen, 2012).~~Heudorfer & Stahl, 2016). The threshold can be fixed or variable~~, but~~; we used the monthly 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).~~

From the comparison between the flow and the threshold, several drought metrics can be calculated. Drought events are defined as consecutive periods of several months of below-threshold flow. We excluded drought events with a duration of only 1 month from the analysis process so that all drought events are longer than the time step of the threshold. The first drought metric used for the paired-catchment comparison is ‘occurrence of drought events’. We calculated the frequency, which is the total number of drought events identified in the time period. The second drought metric analysed is ‘duration of drought events’. We used the total number of months in drought, the average duration of all events, and the duration of the maximum event. The third drought metric is 'deficit volume of drought events', which is defined as the cumulative difference between the flow and the threshold over the drought event. Again we used the total deficit over the entire time period, the average deficit of all events, and the deficit of the maximum event.

2.4 Estimation of the human impact on drought characteristics

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~~occurs on larger spatial ~~scale~~ and ~~short~~ temporal ~~scale, therefore this is less of an issue. However,~~scales, but it can still be ~~limiting~~challenging to compare ~~one off~~single events ~~(e.g. in the case of droughts ending by localised rainstorms), therefore here~~. Therefore, we ~~have analysed~~focus on the changes in the average and maximum drought ~~metric~~metrics over a longer time period rather than on 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~~mentioned in ~~drought~~Section 2.3 were obtained from the drought analysis ~~for~~applied to each ~~paired~~ catchment~~. To calculate the human influence~~ and then compared between the ~~two~~paired catchments~~,~~. The difference between the ~~natural catchment~~ drought metrics ~~and~~of the human-influenced catchment ~~metrics (Figure 1)~~ and those of the benchmark catchment (Fig. 2) was ~~established~~calculated using the following equation (Eq. ~~(~~1):

*Percentage ~~increase~~change due to the human influence (%) = [(Human – ~~Natural~~Benchmark)] * 100*

(1)

~~Natural~~

~~3. Application of the paired catchment approach~~

~~Here~~ *Benchmark*

3. Case studies

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) ~~in the UK and Australia (Fig. 3) were chosen because ~~both have groundwater abstraction, but~~of their contrasting climate~~ and~~, geology~~.~~, and human activity. The UK case study is impacted by a water transfer scheme, has a temperate maritime climate and a ~~slowly~~relatively slow responding catchment, ~~and ~~the Australian ~~paired catchment ~~case study is impacted by groundwater abstraction, has a semi-arid climate and ~~a flashier catchment.~~faster response times. These case studies were chosen based on the availability of data required for the assessment and analysis, including qualitative information on the human activities occurring in the catchments. For both human-influenced catchments we then applied the catchment selection scheme in Fig. 1 to find a suitable benchmark catchment.

Table ~~2 outlines~~1 contains the main information about the two sets of 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 (Fig. 1, 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~~1 UK paired catchments: ~~Kennet~~Blackwater and ~~Dun~~Chelmer

~~It is known that ~~*3.1.1 Paired-catchment selection*

The Blackwater catchment receives water ~~abstractions affect streamflow~~transfers as part of the ~~river Kennet, a catchment in Southern England (Dunbar~~Ely Ouse water transfer scheme for the greater London area (NRFA, 2018; Tijdeman et al., ~~2002). The Kennet is a catchment underlain~~2018). The scheme was introduced in 1972 by ~~chalk~~the Environment Agency to help address anticipated water stresses due to population increase and ~~is reported to be predominately rural, with a market town close to outfall (NRFA, 2017). The Kennet was ~~expansion and development in the South Essex area (AEDA, 1990). The Blackwater catchment was paired with a ~~similar catchment ~~nearby catchment (Chelmer; Fig. 3) as its ~~natural pair, the Dun (Figure 2),~~benchmark, due to ~~its~~their similarity in catchment characteristics (Table ~~2). The Dun is also a chalk dominated, rural catchment with an ~~1). Both catchments have a geology of mixed permeability superficial deposits (86-88%), a predominantly rural land use (Fig. 3) and similar 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).~~totals (within 10%) (Table 1). Both catchments have very low urban extent ~~(<3%) ~~(Chelmer 4.9% and Blackwater 5.4%; NRFA, 2018) and the land uses are very similar, with arable land covering 71% - 75% in both (NRFA, ~~2017~~2018; Fig. 3). The observation data available for both catchments ran from ~~1973~~1972 to ~~2013~~2015 with no missing data, covering a number of important drought events in the UK.

3.1.2 Drought comparison results

The drought analysis ~~using the paired~~ shows that many droughts experienced in the natural catchment ~~approach showed an aggravation in all drought metrics~~ were alleviated in the human catchment due to the ~~human activity, especially~~water transfer scheme (Fig, 4; Table 2). Notably, the 1976 UK drought was not as severe in the Blackwater catchment as its benchmark pair. A number of other major drought events occurred in Chelmer in the 1990s and 2003 were not seen in Blackwater, therefore showing that they were alleviated due to the elevated flows from the water transfer scheme (Fig. 4). The largest alleviation is seen in the total number of months ~~spent~~ in drought~~,~~ and the ~~maximum drought~~total deficit over the time series (Table 2), while the average 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~~ decreased less due to the water transfer. This shows that the water transfer mainly reduced the number of droughts 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~~2 Australian paired catchments: Cox and Cockburn

3.2.1 Paired-catchment selection

The Cox catchment in south-eastern Australia has heavy groundwater abstraction for irrigation (Ivkovic et al., 2014). For the paired-catchment analysis, the ~~natural~~benchmark catchment, Cockburn, was chosen based on its similarity in precipitation and geology (Table ~~2~~1) and its proximity (~~Figure 2~~Fig. 3). BFI for the ~~natural~~benchmark catchment is much lower than that of the UK ~~natural~~benchmark catchment, showing that the Australian catchments are responding faster to precipitation (Table ~~2~~1). Observation data was available from 1982 – 2013, with no missing data.

The land use in both catchments is similar (see Fig. 3). Both catchments have a mix of natural savannahs and grassland used for grazing (Cox: 59%, Cockburn: 53%), with natural land cover composed of woody savannah (Cox: 32%, Cockburn: 28%) and forest (Cox: 6%, Cockburn: 13%). According to Green et al. (2011) the Cox catchment land use is “a combination of grazing and dryland cropping with agriculture”. The benchmark catchment, Cockburn, is described as “the area is mainly used for grazing with some dryland cropping and horticulture” (Green et al., 2011). The only difference between the catchments is the heavy groundwater abstraction in the Cox (Ivkovic et al., 2014), which is the human influence we are aiming to quantify.

3.2.2 Drought comparison results

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~~total deficit (~~Figure 4~~Fig. 5, 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.~~ 3). The well-documented Millennium Drought in Australia (2001 – 2009; Van Dijk et al., 2013) ~~is shown~~shows 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).~~benchmark catchment (Fig. 5). Like the water transfer in the UK case study, the water abstraction in Australia mainly results in more frequent drought events, not so much in more severe drought events. The maximum drought event characteristics are probably not affected (Table 3) because during these rare events the flow is zero in both cases.

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~~.~~ using observation data. There are limitations to this approach, as any observation- and/or ~~modelling~~ model-based approach has uncertainties. ~~Modelling~~Model-based 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 (McMillan et al, 2012; Coxon et al, 2015). Also, isolation of one type of human-influence is often more difficult in observation data.

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:~~ characteristics: climate (precipitation, potential evapotranspiration), geology, and ~~PET (Table~~land use (Fig. 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~~most important drivers of hydrological 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~~in the analysis of low ~~flow studies~~flows 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 effect of human influence from the effects of geological differences.

~~With regards to precipitation,~~ Similarity in precipitation is important as it is the driving meteorological factor~~.~~ for drought development. Both precipitation variability and annual averages should be similar for the paired catchments (~~Table~~Fig. 1). Firstly, it is important that the total precipitation inputs are similar for both catchments because of the cross use of the ~~natural~~benchmark catchment threshold~~.~~ (Fig. 2). Significantly higher or lower precipitation in the ~~natural~~benchmark 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~~ If we want to increase our understanding of the effect of different human activities ~~can be done best when isolating~~on drought, we need to isolate the human influence under study. Here the focus was on the human ~~activity of~~activities of adding water via water transfer and removing water via 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~~Traditional paired-catchment experiments usually include a ~~specific~~ pre-disturbance period ~~for calibration and~~ to assess the similarity of the catchments before treatment. 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~~catchments (Folton et al., 2015), therefore a pre-disturbance period can possibly offer a quantification of ~~their~~these differences, e.g. through a regression equation (Hornbeck et al., 1993; Bari et al., 1996). However, generally this ~~does assume~~assumes a linear relationship between the ~~pairs~~catchments, 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~~ and the human activity started before the hydrological measurements (Peñas et al., 2016). Peñas et al. (2016) tested the paired-catchment approach without pre-disturbance period to that with pre-disturbance period and found that over 80% of the impacted hydrological variables were identified correctly by the approach without pre-disturbance period and, therefore, suggest to use this approach when no pre-disturbance data are available.

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~~ benchmark catchment, which is identical to the human-influenced catchment ~~where~~except for the human ~~influence is the only difference~~activity. 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~~undisturbed by the human activity under study and should then not be used in a paired-catchment analysis~~ of the effect of groundwater abstraction.~~. Instead, we suggest to compromise on another selection criterion (~~Table~~Fig. 1), such as precipitation, to locate a suitable ~~natural~~benchmark 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~~a need for information on the type and extent of human disturbance ~~within the data~~, which may not always be available or known~~.~~ (Fig. 1). Differences in drought between the catchments cannot fully be attributed to the human influence, as there will always be a remaining uncertainty in the catchment pairing. However, the approach can be used for a first estimate of the human influence on drought, to steer campaigns to collect more data, and to complement other existing methods (e.g. model-based and observation-modelling approaches).

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 from this could be to use data from published paired ~~catchments~~ catchment studies, 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~~option 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~~In this study, 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~~,~~ and geology), and identified the advantages and limitations of the approach. The main advantage ~~of the approach~~ is that ~~it compares~~automatically the same time periods are compared, 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~~of 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~~regard to input data and catchment ~~similarities~~similarity, it is important to note that these uncertainties are similar to ~~existing~~other 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~~pre-existing and long-term human impact on hydrological droughts. We have used the method to analyse the impact of water transfer and groundwater abstraction in contrasting climate and geology settings. The example case studies ~~analysed of~~in the UK and Australia clearly show an alleviation and aggravation of drought, respectively, due to the human activity compared to the ~~natural~~benchmark catchment. However uncertainties remain in attributing these differences ~~in~~to the human influence

~~between the two case studies are seen~~under study, 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 hydrological droughts, this knowledge can then be used for water resource management and for improving hydrological modelling.

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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)~~

~~Table 2: ~~Catchment data ~~about each~~of the paired ~~catchment~~catchments of both case ~~study.~~studies

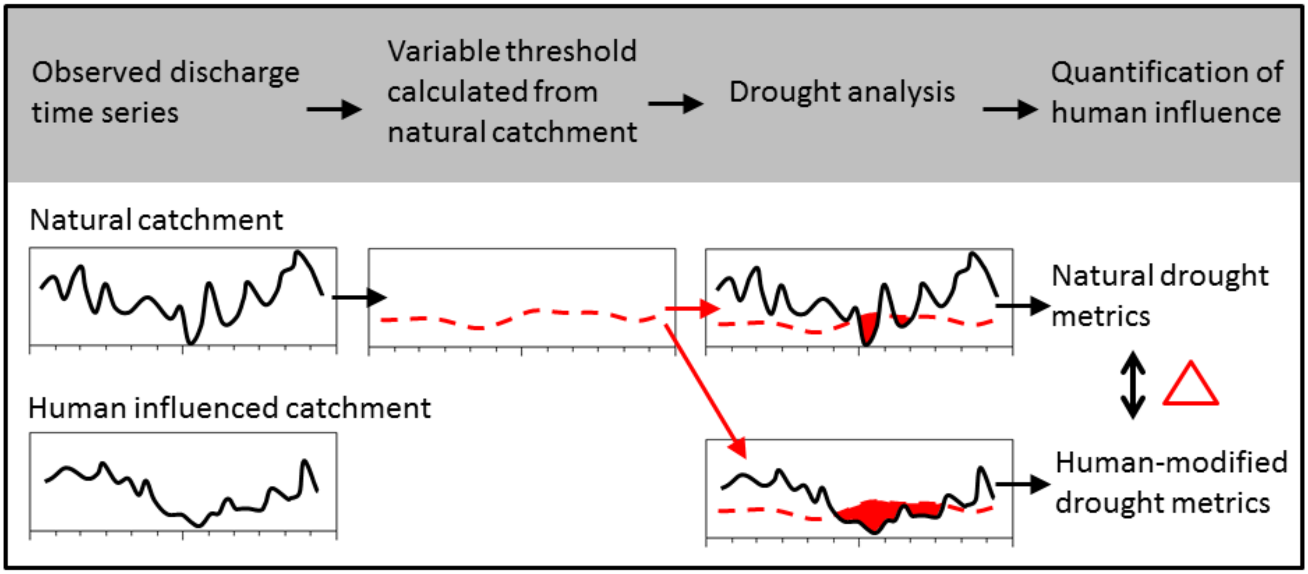
Case study	Human activity	Catchment status	River/ Station	Catchment area (km^2)	Geology	Average annual precipitation (mm)	Average annual flow (mm)	BFI
UK	~~Ground water abstraction for public water supply and agriculture~~Water transfer scheme	~~Natural~~Benchmark	~~Dun (39028 Hungerford station)~~Chelmer (37011 Churchend)	~~101.3~~72.6	~~Mainly~~London clay and chalk~~ based (some clay ~~, overlain with~~ flints)~~ Boulder Clay	~~829~~591	~~218~~91	0.~~954~~3
		Human	~~Kennet (39037 Malborough station)~~Blackwater (37017 Stisted)	~~142~~139.2	~~Chalk dominated (some~~London clay~~-~~ and chalk, overlain with~~ flints)~~ Boulder Clay	~~838~~579	~~196~~194	0.~~94~~5
Australia	Ground water abstraction for irrigation	~~Natural~~ Benchmark	Cockburn (419016 Mulla Xing station)	907	Alluvial overlying fractured rock (granite and sedimentary)	665	64	0.24
		Human	Cox ~~(~~ (419033 Tambar Springs station)	1450	Bedrock-contained alluvial valley	732	21	0.21

Table ~~3~~2: Paired-catchment ~~analysis~~ results for UK, ~~Kennet~~Blackwater (Human) and ~~Dun (Natural~~Chelmer (Benchmark).

	Occurrence	**Duration (months)**			**Deficit (mm)**		
	Frequency	Total ~~no. of months in drought~~duration	Average duration ~~(months)~~	Maximum duration ~~(months)~~	Total deficit ~~(mm)~~	Average deficit ~~(mm)~~	Maximum deficit ~~(mm)~~
~~Natural~~ Benchmark	~~15~~22	~~93~~86	~~5.8~~3.9	~~13~~10	~~224.3~~163.8	~~12~~7.4	~~47~~29.6
Human	~~31~~7	~~243~~16	~~7.8~~2.3	~~30~~4	~~1210.9~~39.3	~~39.1~~5.6	~~186.2~~16
% ~~increase~~difference due to the human influence	~~+107~~ -68%	~~+161~~ -81%	~~+35~~ -42%	~~+131~~ -60%	~~+440~~ -76%	~~+179~~ -25%	~~+291~~ -46%

Table ~~4~~3: Paired-catchment results for Australia, Cox (Human) and Cockburn (~~Natural~~Benchmark).

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


Observed discharge time series
Variable threshold calculated from natural catchment
Drought analysis
Quantification of human influence
Natural catchment
Natural drought metrics
Human influenced catchment
Human-modified drought metrics

~~Figure 1~~

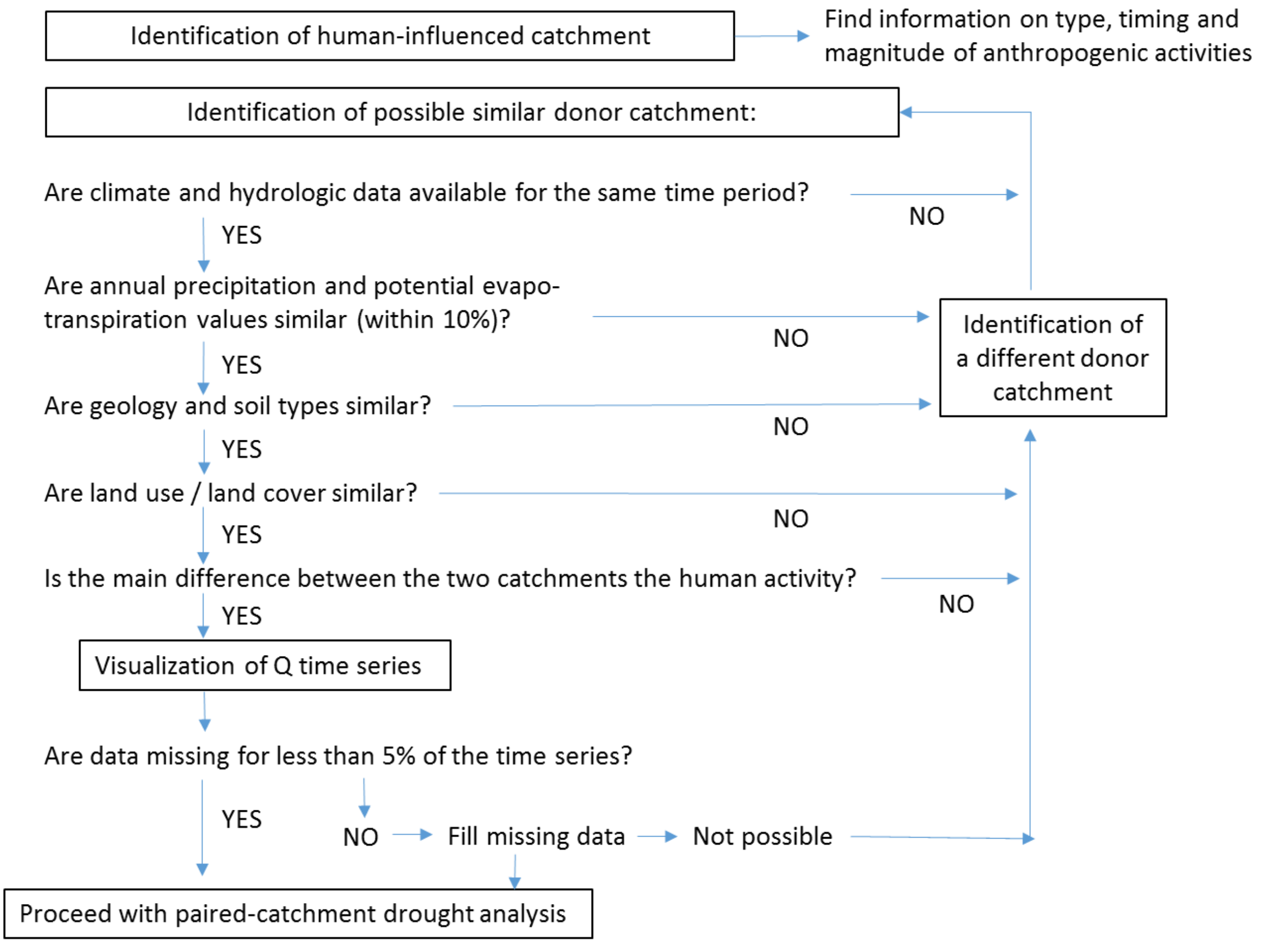


Figure 1: Flow diagram for choosing paired catchments for analysis of the human influence on hydrological drought.

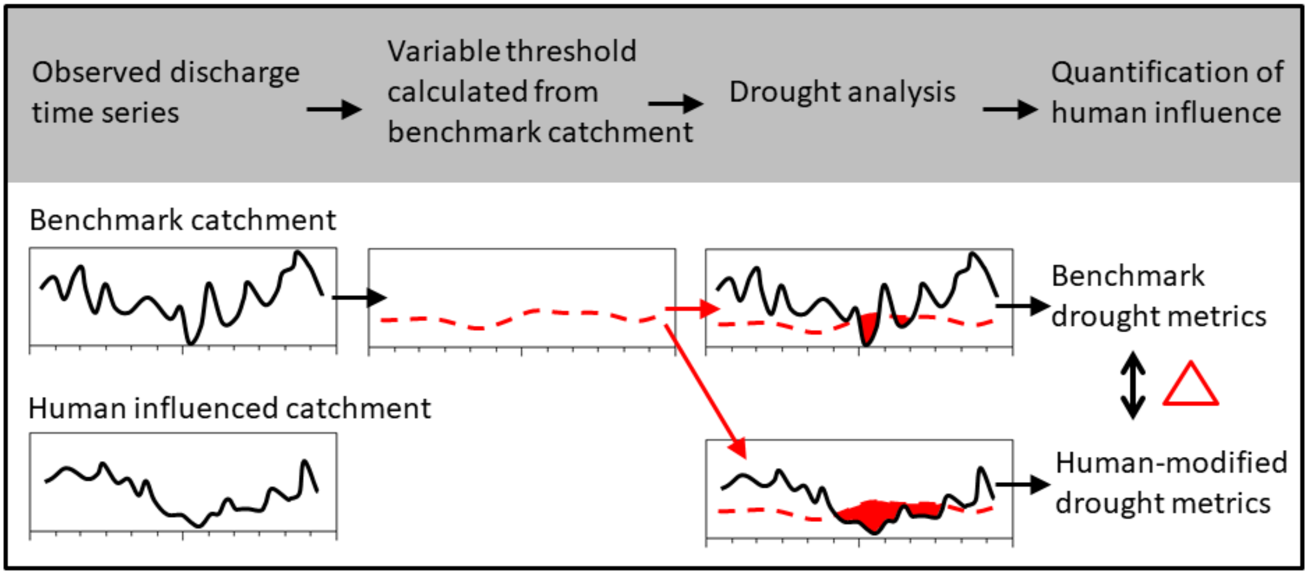
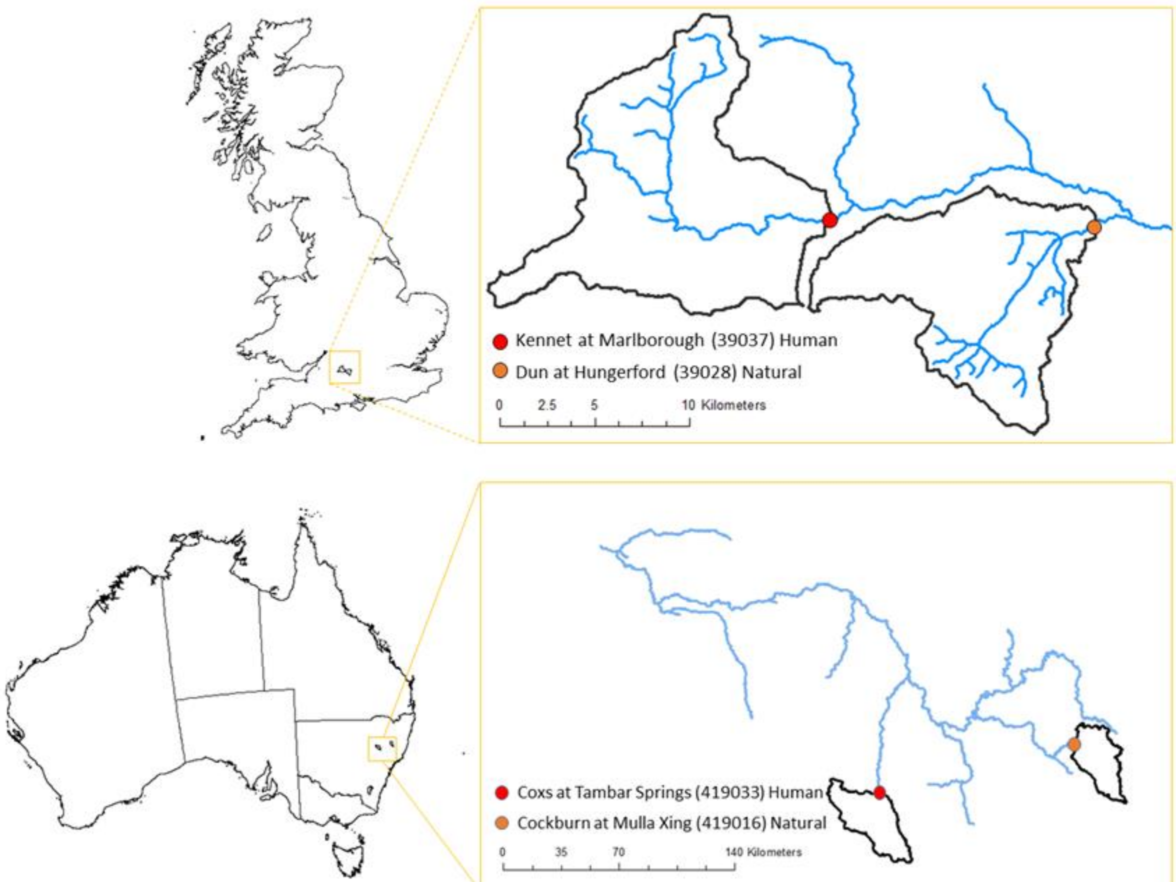


Figure 2: Diagram of the drought analysis method and quantification of the human influence on the hydrological drought metrics.


Kennet at Marlborough (39037) Human
Dun at Hungerford (39028) Natural
0 2.5 5 10 Kilometers
Coxs at Tambar Springs (419033) Human
Cockburn at Mulla Xing (419016) Natural
0 35 70 140 Kilometers

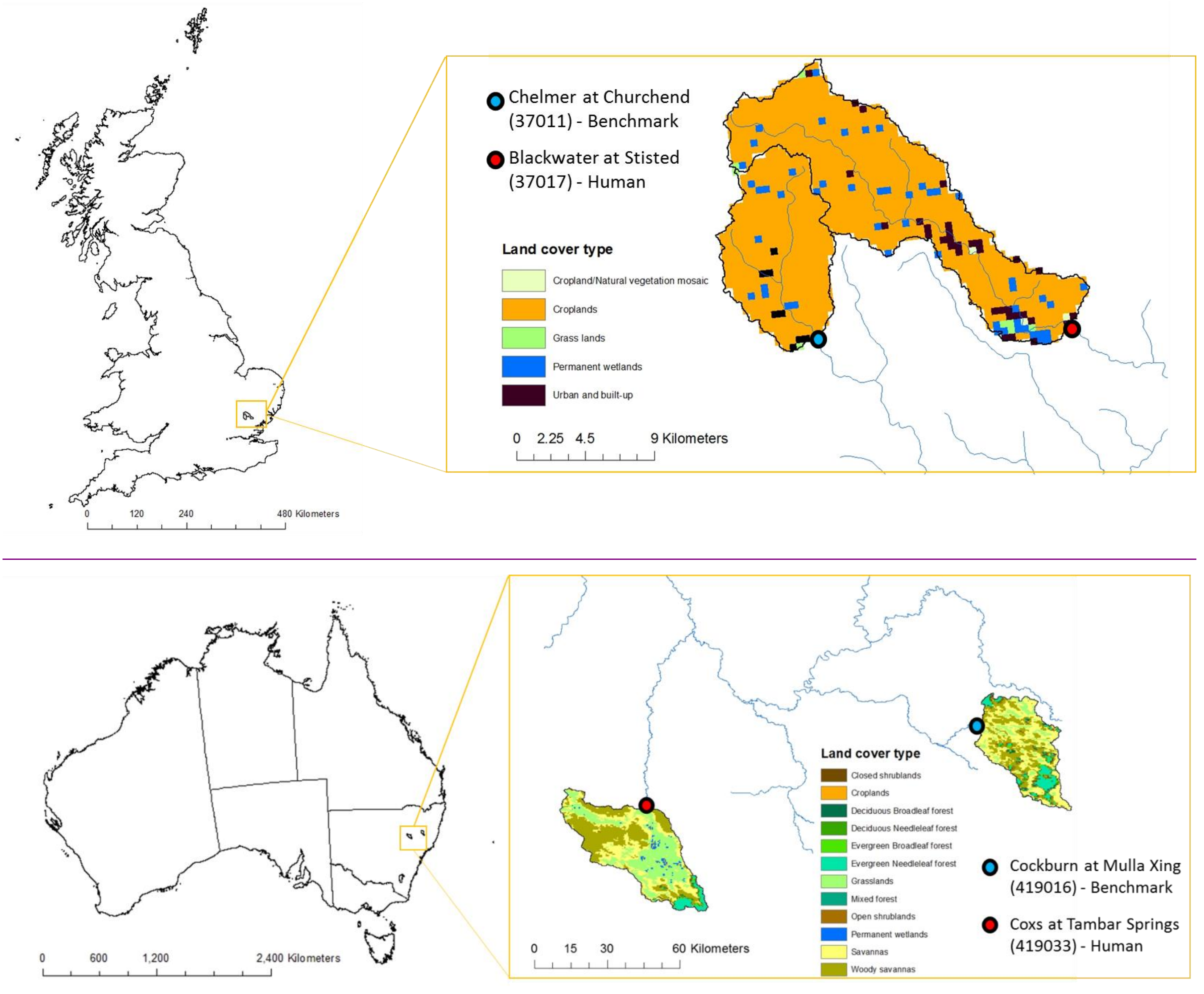
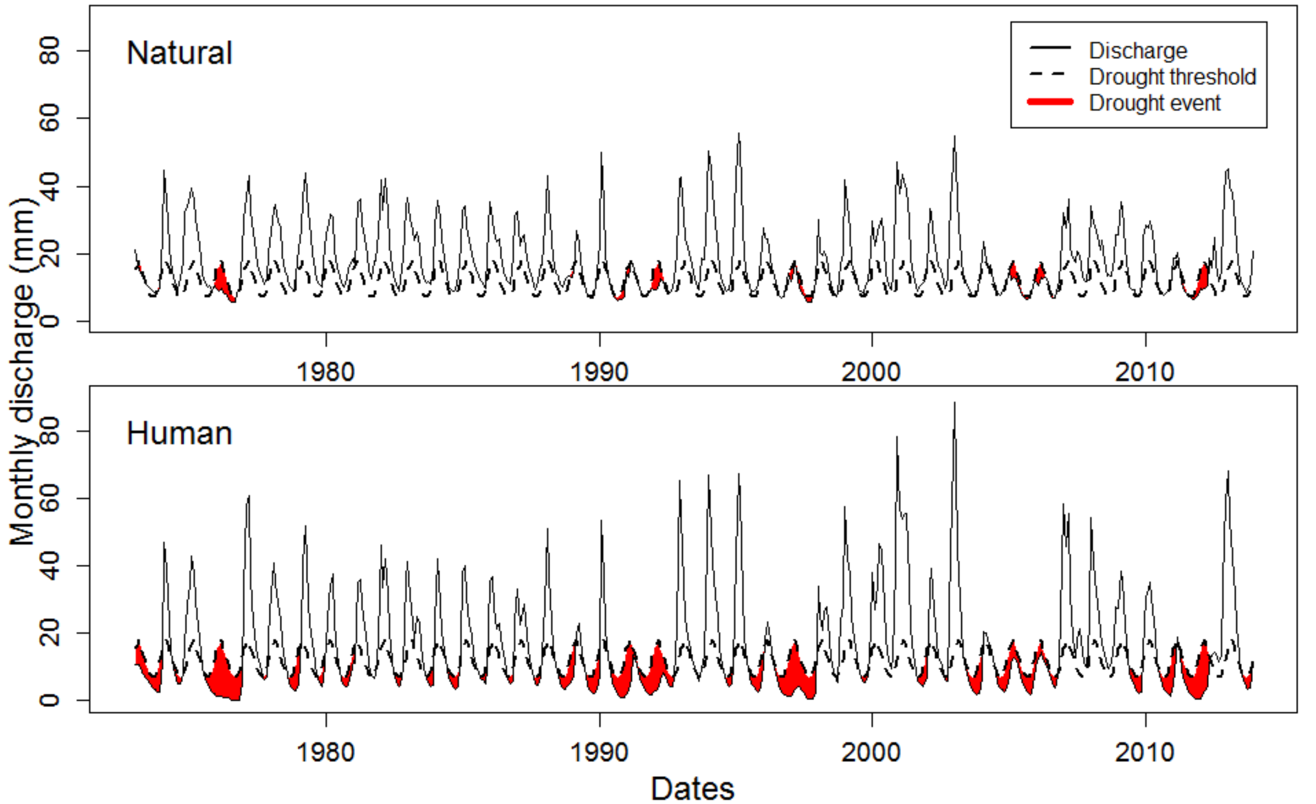


Figure ~~2~~3: Paired-catchment case studies in the UK (top) and Australia (bottom~~).~~), including the location of the gauging station and land use.


Natural
Discharge
Drought threshold
Drought event
Human
Monthly discharge (mm)
0
20
40
60
80
1980
1990
2000
2010
Dates

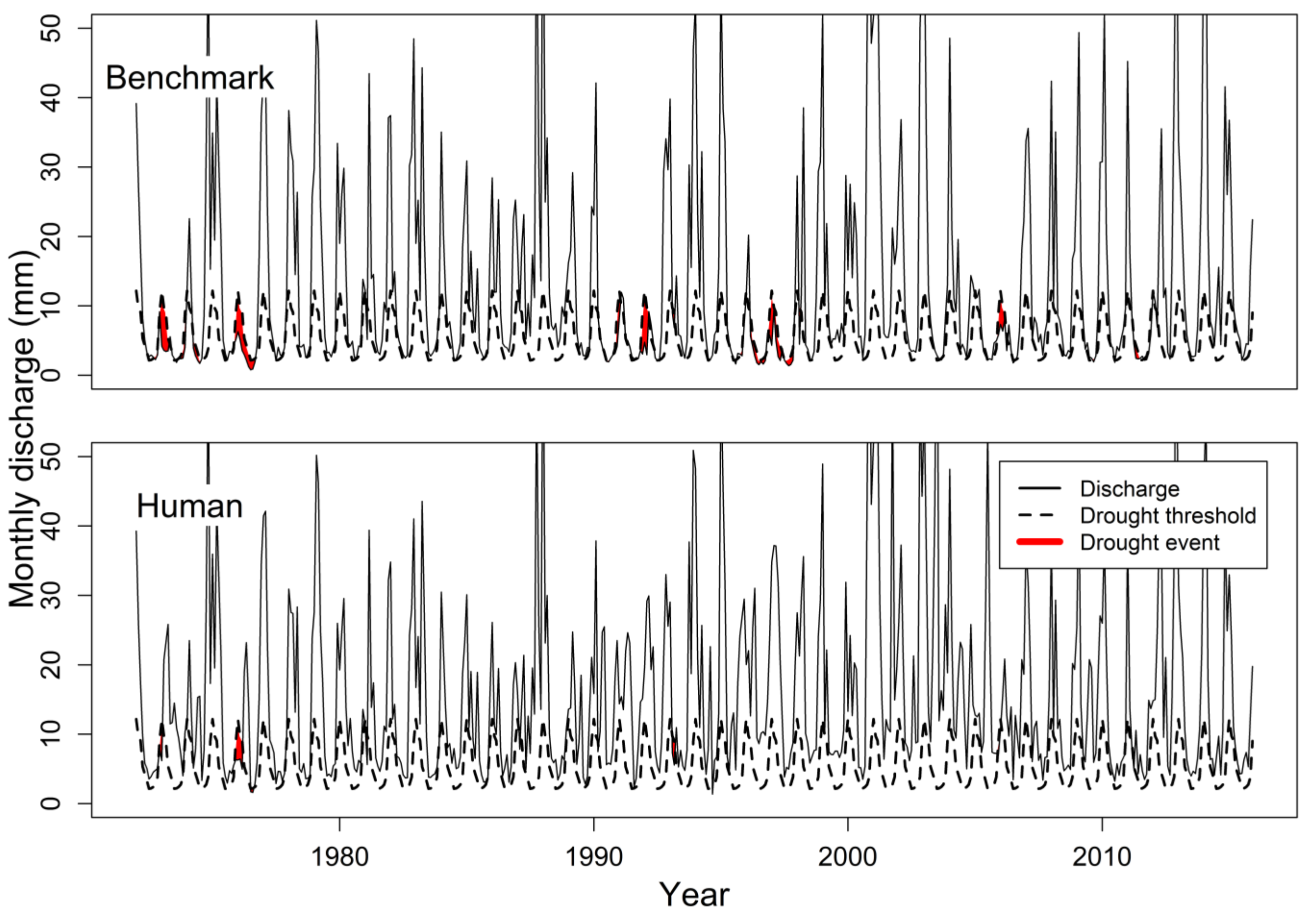
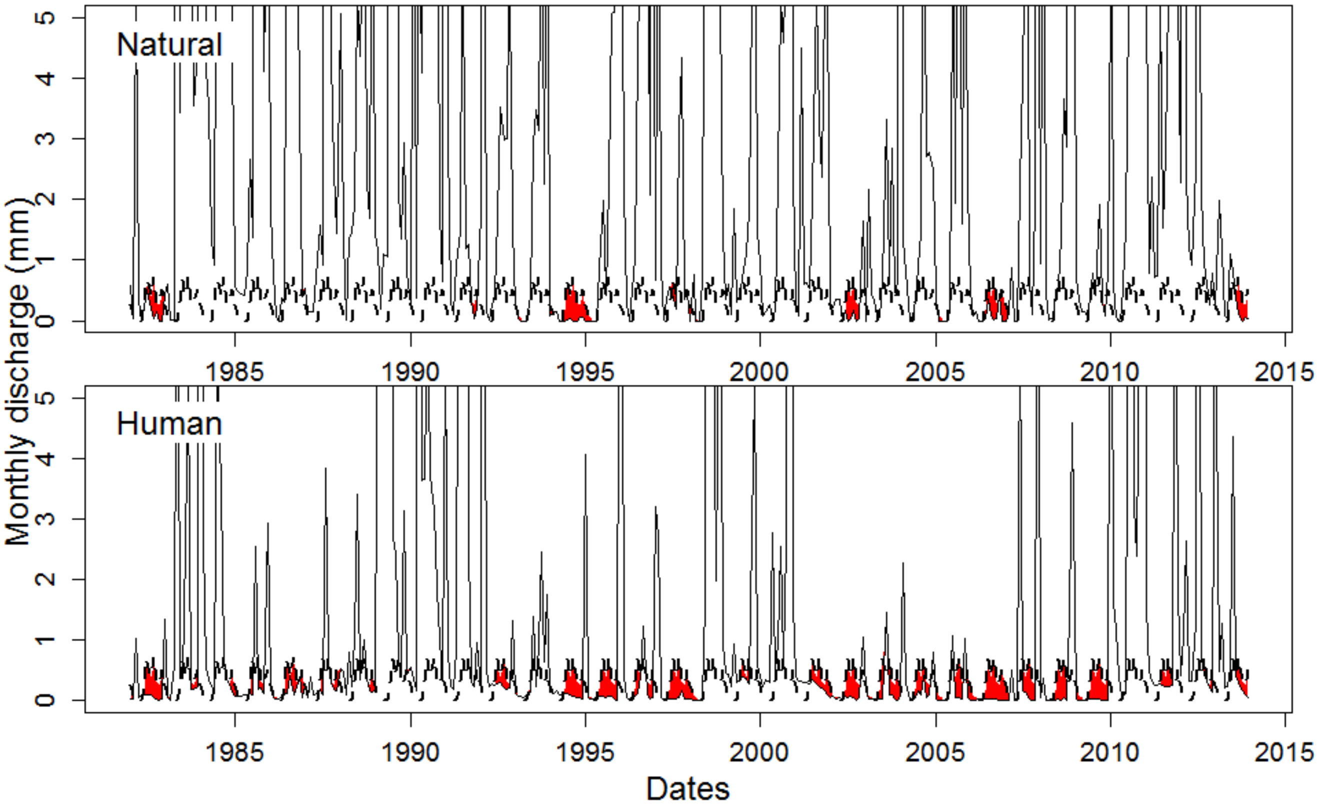


Figure ~~3~~4: Drought analysis results for the UK pair, ~~Kennet~~Blackwater (human) and ~~Dun (natural) (1973 – 2013).~~Chelmer (benchmark) (1972 – 2015). Black solid line represents streamflow, dashed black line represents ~~80%~~Q80 variable threshold, and red areas are identified drought events.


Natural
Human
Monthly discharge (mm)
Dates
0
1
2
3
4
5
1985
1990
1995
2000
2005
2010
2015

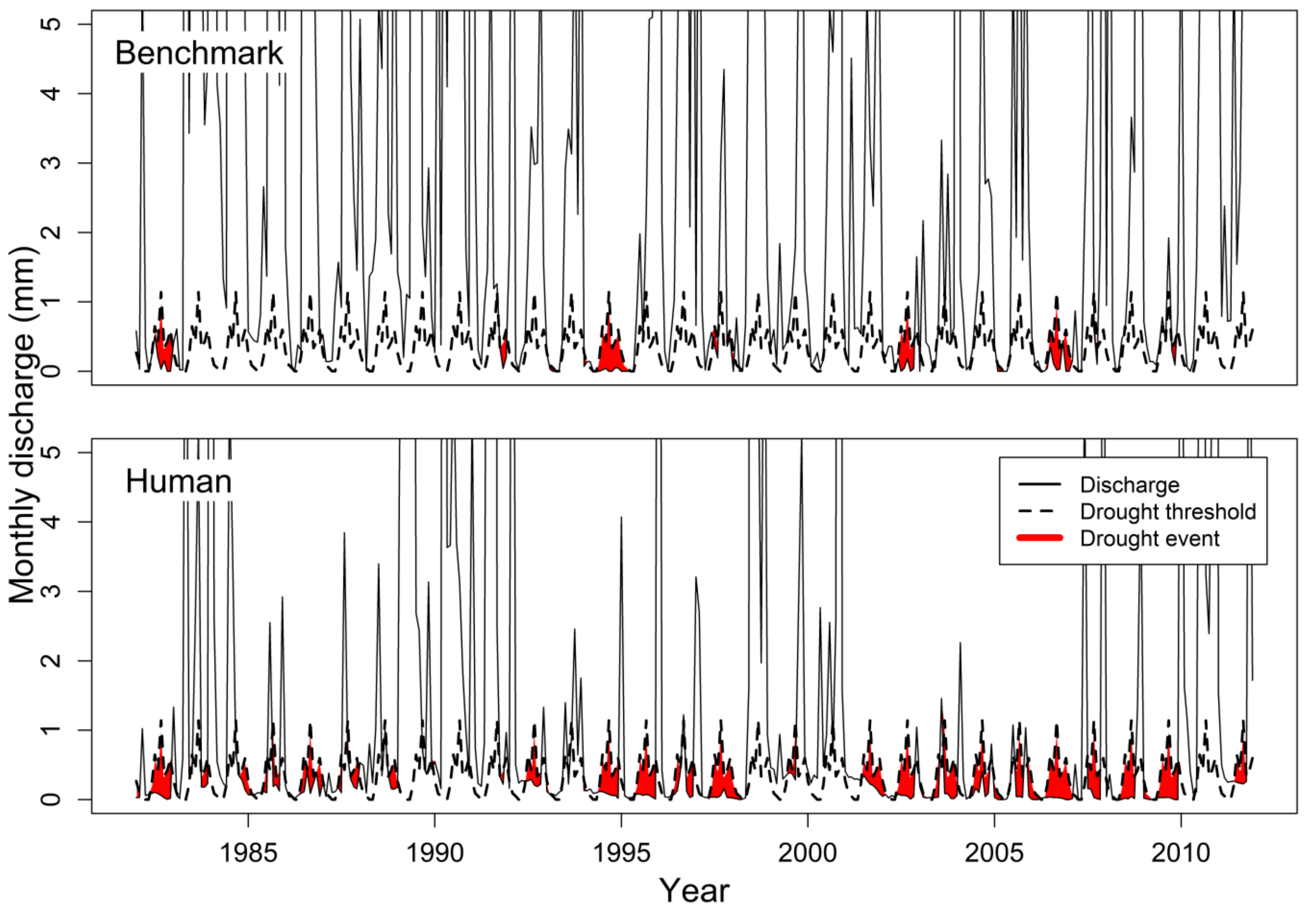


Figure ~~4~~5: Drought analysis for the Australian pair, Cox (Human) and Cockburn (~~Natural~~Benchmark) (1982 – 2013). Flow higher than 5 mm/month is not shown. Black solid line represents streamflow, dashed black line represents 80% variable threshold, and red areas are identified drought events.