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Discussions

Interactive comment on "Nonstationarity of low flows and their timing in the eastern United States" *by* S. Sadri et al.

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We thank the referee for the very useful comments and suggestions. We have repeated the comments below and our responses are prefaced by the word "Response".

Anonymous Referee #3

This work deals with the analysis of trends and step changes in low flow statistics at stations over the eastern part of the US, and attempts to relate findings to qualitative USGS flags. Although of scientific and operational interest, this study has some weaknesses that prevent its publication in HESS in the present form. My comments had been mainly drawn before the publication of other comments in the online discussion, but I can see that many of my points overlap with previously made ones.

In summary, I would suggest to investigate in much more detail the qualitative flags used and check the meaning of “no flag” for each station, all of this necessarily in close cooperation with USGS database managers. This would contribute to improve the conclusions in terms of relations between statistical findings and human disturbances. My two main comments are detailed below, followed by a list of more specific comments.

General comments

Understanding of the hydrometric database The manuscript shows many examples of misunderstanding of the database flags, the most noticeable being the “change in gauge datum”. This seems to reflect a lack of investigation on the meaning of these flags. More generally, such a study should be done in close cooperation with the database managers and field hydrologists. In that sense, the hard work made to identify reference hydrometric networks should be recognized, and more critically, used.

Response: We agree that closer cooperation would provide benefits. During the development of the study, we consulted with colleagues who had been using the flag information for studying changes in peak flows. We do acknowledge that the discussion of the flags and their use in interpreting the identified changes in low flows needs to be adjusted to better reflect the meaning of the flags. See responses to referees #1 and #2.

Below are some related comments on specific parts of the manuscript:

1. P2770 L3-6: The big question here is: What is the default in the database? Indeed, what is the meaning of a station with no flag? Is it actually a station with minor anthropogenic influence or change, or may it be a station that has not been documented (yet)? I know that other hydrometric databases include stations that are not flagged (by lack of time for a comprehensive overview) but should be. This is an issue that is not even mentioned in the manuscript, while it may have serious consequences on the interpretation of results.

Response: Table 1 shows that there are many sites that are identified as having statistically significant step changes (which are potentially due to some form of anthropogenic influence or change in how flows are measured – or possibly a climate regime shift) but do not have a USGS flag. The point of Table 1 is to show that the step changes identified are generally consistent with the USGS flags, but that there are also many changes that are not – there are multiple reasons for this as mentioned in the manuscript and by the referee here, including that the flags have not yet been assigned or that the anthropogenic impacts are small. We discuss the uncertainties with using the database, and the possible errors, in response to other referee comments.

2. P2770 L9-11: "The sites in the mid-Atlantic states are generally more affected by [...] change of gauge datum": This sentence implies that a change of gauge datum can be interpreted as a change in the catchment hydrological behaviour. Well, this is simply a change in the reference level for measuring water levels at the station. Besides, the list of flag you mention does not include dates of changes in the rating curve, which may have consequences in computed streamflow values, mainly for stations with unstable riverbed.

Response: Agreed. The original wording in the manuscript does imply that this is related to a change in the catchment response, which is incorrect. We have edited this sentence in response to other referees' comments. The flags in the USGS database do not include information on changes in rating curves and so this is another uncertainty – we have added this to the discussion of the streamflow data in section 2.2: "Changes in the rating curve used to estimate streamflow from measured water levels are not recorded in the USGS notes but may be a significant source of variation in low flow values that is not accounted for."

3. P2773 L21-26 "this is mostly associated with a change in gauge datum" (and similar quotes): Again this serious issue of interpreting the "change in gauge datum" flag. P2774 "If a site is flagged and its low flow series has a decreasing trend, this is mostly associated with a change of gauge datum" "if a site is flagged and its low flow series has

an increasing trend, this is mostly related to regulation or a change of gauge datum"

Response: Again, we have edited these sentences in response to other referees' similar comments.

Relating human disturbance and trends or step changes There are several assumptions in the interpretation of trends and step changes in terms of potential causes that are clearly debatable and that undermine the overall conclusions. Indeed, gradual changes may for example come from either the climate or gradual changes in water abstractions and water management. A step back should be taken to consider all possible causes (climate, water abstraction, water management) to statistical findings. Below are some related comments on specific parts of the manuscript:

1. P2767 L14-16 "We therefore assume that step changes in the time series are indicative of an anthropogenic effect, and that gradual trends reflect a climate effect": This is a very strong assumption, and if climate change may indeed mainly cause gradual changes, this is also the case for different anthropogenic actions on the catchment. Examples of such actions can be found in the manuscript itself, for example P2768 L6-16, where you list a number of land cover / land use changes that gradually change the catchment hydrological behaviour. Similar comments may also be applied to gradual increase in water withdrawals, be they for drinking water following urbanization and population growth or for irrigation.

Response: See our response to referee #1.

2. P2772 L16-17: "Is a statistically significant step change is not identified, we assume that the autocorrelation is a reflection of management effects". Well, this is again a very string assumption. Indeed, autocorrelation may come from natural long-term memory from e.g. aquifers.

Response: See our response to referee #1 on this same point.

3. P2776 L22: "regulation" What do you precisely mean by regulation? Regulation

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may for example aim at sustaining low flows above a given absolute level (for e.g., environmental flows), and this would have in this case a strong effect on Q1day or Q7days, but a limited effect on more temporally integrated indices like Q90days.

Response: We assume the referee is referring to P2775 L22. We have removed “regulation” from this sentence to be consistent with the slightly altered description of the assumptions about abrupt step changes. Please see earlier responses. “We further examined the consistency of the change year among the Qn series, with the expectation that abrupt changes caused by regulation would be identified for the same year across all or most Qn time series.”

4. P2777 L4: “rather than a direct anthropogenic impact on the low flows” Again it is not clear what you mean by “direct”. I could understand “indirect” through the consequences of anthropogenic climate change. But “direct” in my opinion applies to all human disturbances on the natural catchment hydrological behaviour, whether on land cover/ land use change, water management change, or combination of both.

Response: By “direct” we mean that the flows are manipulated directly through management. To be clear we have updated the sentence: “The attribution of trends at these sites is therefore likely related to climate variability/change and/or land use change, rather than management of flows.”

Specific comments

1. P2764 L4-6: I don’t understand why the two facts should be conflicting. Please rephrase.

Response: Agreed. We changed it as follows: “Surface water covers 4.5 % of the eastern US, and the majority of streams have been flagged by the US Geological Survey (USGS) as regulated”

2. P2764 L16: I’m not sure that the reference used here is the most relevant one to support your statements.

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Response: The original reference cites numerous examples of the anthropogenic influences on low flows (although mostly with respect to ecological impacts) and we have chosen some examples to better directly support these statements. We have also added some other relevant references: “Generally dams and reservoirs are considered the largest man-made regulations on streamflow, but other sources include farm ponds, surface water extraction, inter-basin transfers, and wastewater treatment plant discharge (e.g. Walker and Thoms, 1993; Acreman et al., 2000; Brandes et al., 2005; Thomas, 2006; Deitch et al., 2009; Kustu et al. 2010).”

Acreman, M. C., B. Adams, and B. Connorton, 2000: Does groundwater abstraction cause degradation of rivers and wetlands? Water and Environment Journal, 14, 200–206.

Brandes, D., Cavallo, G.J., Nilson, M.L., 2005: Base flow trends in urbanizing watersheds of the Delaware River basin. J. American Water Resources Association, 41 (6), art. no. 04114, pp. 1377-1391. doi: 10.1111/j.1752-1688.2005.tb03806.x

Deitch, M. J., G. M. Kondolf, and A. M. Merenlender, 2009: Hydrologic impacts of small-scale instream diversions for frost and heat protection in the California wine country. River Research and Applications, 25, 118-134.

Kustu, M. D., Y. Fan, and A, Robock, 2010: Large-scale water cycle perturbation due to irrigation pumping in the US High Plains: A synthesis of observed streamflow changes. J. Hydrol., 390 (3-4), 222-244. doi:10.1016/j.jhydrol.2010.06.045

Thomas, B., 2006. Trends in Streamflow of the San Pedro River, Southeastern Arizona, U.S. Geological Survey Fact Sheet 2006-3004, 4 pp., http://pubs.usgs.gov/fs/2006/3004/, accessed April 2011.

Walker, K. F. and M. C. Thoms, 1993: Environmental effects of flow regulation on the lower river Murray. Australia. Regul. Rivers: Res. Mgmt., 8, 103-119. doi: 10.1002/rrr.3450080114

3. P2768 L21: Could you elaborate on the "lake-effect snow"? I'm not sure any reader is familiar with it (I am not).

Response: We deleted this sentence.

4. P2769 L8: "(EPA, 2008)": Could you provide any primary and recent literature on this? We have added a reference to Hayhoe et al. (2007), which documents historic and future projected changes for the eastern U.S.

5. P2770 L23: Is it the day with the minimum low flow? Please confirm.

Response: It is based on the Q7 dates. We updated the text: "We also calculate the day of the year of low flows and use this to identify the primary (and in some regions the secondary) low flow season, as well as any long-term changes in timing. The timing results are shown based on Q7 flows."

6. P2771 L1: I assume you wanted to write "A sequence of realizations of a random variable"

Response: Yes. We updated the text.

7. P2771 L7-9: Please define "i".

Response: This denotes one realization of the random variable: "with i representing one realization of a time series."

8. P2771 L14-16: Well, this may be true if you have a long enough series, which is rarely the case in hydroclimatology where the quest for understanding natural variability is still ongoing. Plus, I would strongly suggest using hydrological textbooks or papers rather than finance ones as reference works in order to better capture the specificities of the field.

Response: We updated this section to better reflect the general statistical and hydrological literature (also including updates in response to other comments): "A sequence of realizations of random variables, Y, is stationary if the distribution of the sequence is

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independent of the choice of starting point (Kendall et al., 1983; Ruppert, 2011). Determining stationarity of a time series is not straightforward (Lins and Cohen, 2011) and in practice, it is common to look at restricted measures of stationarity. A time series is defined as weakly stationary if it satisfies three criteria: [equations here] where μ is the sample mean, σ is the standard deviation and is the correlation, with i representing one realization of a time series. This means that for a weakly stationary variable, the mean and variance do not change with time and the correlation between two values depends only on the lag (the time between values). Visual inspection of the time series and the changes therein can be very helpful in determining stationarity, in that a change in the underlying process leads to changes in values that are obvious (Lins and Cohen, 2011; Koutsoyiannis, 2011)"

Kendall, M., A. Stuart, and J. K. Ord, 1983: The Advanced Theory of Statistics, Vol. 3, Design and Analysis, and Time Series, 4th ed., 780 pp., Oxford Univ. Press, New York.

Koutsoyiannis, D., 2011: Hurst-Kolmogorov dynamics and uncertainty. J. American Water Resources Association, 47 (3), 481-495

Lins, H. F. and T. A. Cohn, 2011: Stationarity: Wanted Dead or Alive?. J. American Water Resources Association, 47: 475-480. doi: 10.1111/j.1752-1688.2011.00542.x

9. P2773 L9-11: "therefore a large number of sites appear stationary": why should there be a causal relationship here? 90 days is only one season and there may be trends/changes occurring on one season only. Please rephrase.

Response: We have changed this sentence slightly: "As we move from Q1 to Q90, a larger number of sites appear stationary (category 1) and the number of sites identified using the Pettitt test as having an abrupt shift in the time series (category 4) decreases."

10. Fig. 4: Does it show results from the first step of the algorithm? (I assume it does)

Response: Yes. We have updated the caption and the associated text: "However, there are also many sites in category 1 (45 %; no trend), 2 (34 %; decreasing trend) and 3

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(67 %; increasing trend) that are also flagged (see Fig. 4) " "Figure 4. Categorization of non-stationarity of sites for Q1 with no USGS flags from the first step of the decomposition algorithm."

11. P2776 L1-2: "Q1 may be the most appropriate for identifying a change since they are based on the original time series data": I personally disagree. Indeed, Q1 are more prone to measurement errors at so low water levels than more temporally integrated indices. Q7, or MAM(7) as described by WMO (2008), is much more widely used and in my sense more suitable here.

Response: We have updated the sentence to reflect this: "Although we have identified the change year for all Qn, the results for Q7 may be the most appropriate for identifying a change since the data are close to the original values, but are less affected by measurement errors than Q1 (WMO, 2008)."

12. P2776 L23: There is no grey point in Fig. 7.

Response: This sentence referred to an earlier version of the figure. The sentence has been removed.

13. Fig. 7: There is some inconsistency between (b) and (c). Plus, did you apply here some MK test taking account of autocorrelation?

Response: Yes. The figure has been updated. See response to referee #1 about the autocorrelation.

14. P2777 L 11-12: "If the onset time of the low flow season for a site occurs 70 to 100

Response: The referee comment appears to be incomplete so we cannot provide a response.

15. Section 5.1: I would recommend changing the section title, as there is no formal attribution performed here, only observations of qualitative correlation.

Response: We changed the title to: "5.1. Potential Drivers of Trends in Low Flows"

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Interactive Comment

16. Section 4.3: So If I understand well, you remove from the analysis all sites that have two low flow seasons. This means that you are removing all sites that could see a shift in absolute minimum flow from one season to the other, and which are the most interesting ones, from a process point of view, but also from a water management point of view. This would completely change the pattern shown in Fig. 9.

Response: Our original analysis looked at all sites irrespective of whether there was a single low flow season or not, to explore not only whether timings have shifted within a season but also from one season to another, e.g. in the northeast where warming temperatures have altered the freezing regime – something that we agree is interesting. Unfortunately, there was not space to include this full analysis and so we decided to focus on the sites with a single season to simplify the analysis and presentation of results. In any case, the evidence for shifts in timing between seasons was minimal. We have added a short discussion of this at the top of section 4.3: "Analysis of changes in timing irrespective of the season (not shown) did not show evidence of shifts in timing from one season to another."

17. Fig. 10 (a): What is the "warm season"? Plus, what sites are exactly plotted here? I would assume that only unregulated ones (or at least the ones not flagged as regulated) should be presented here.

Response: This plot showed the results for all sites without step changes. We have updated it to show only sites without step changes and without flags – i.e. those without potential regulation.

Technical corrections

1. Figures: they are all very difficult to read (most notably Fig. 5 and 6, but all others). However, there is redundant information that could be removed to make them bigger: axes across subplots, legends across subplots, etc.

Response: We have removed plots for Q1 and Q90 because they are very similar to the results for Q7 and Q30, respectively, and have updated the text throughout. This has enabled us to expand the size of the panels in Figures 5 and 6. We have also edited the other figures where possible to make them easier to read.

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