Author Response to Reviewer 1

Major comments

1. I have some concerns about the title of the paper. It is not really specific and the “42 years” will be only valid for this year 2019, that is not a good choice, I think. It would be better to include the difference between analyzing dQ/dt-Q-point clouds and individual recession. By the way, the paper is not about “recession analysis” (as there are many other recession analysis techniques out there, e.g. master recession curve), so the focus on the dQ/dt-Q-cloud could be emphasized in the title.

Authors Reply: Thank you for this important point. We agree that the current title is limited by including the time stamp. We have greatly modified the title to reflect the motivation and conclusions presented in this paper. The updated title is: Recession Analysis Revisited: impacts of climate on parameter estimation

2. Is the difference between slope b from the point cloud and slope b from median individual b a function of the recession extraction criteria (e.g. longer than 5 days, cut the first day, etc., P02L26). By the way, have the recession a minimum of 5 days with or without the removed first day? Brutsaert and Nieber 1977 also used rainfall data to extract recession segments. . . The recession extraction should be clearly stated in the methods (not only in the Introduction).

Authors Reply: In the revised paper we have included a new methods section (section 2.2) about parameter extraction methods where we have given more details. First, we have included citations of previous studies that have looked at the sensitivity of recession extraction on parameter estimation [*B. Chen & Krajewski*, 2016; *D. N. Dralle et al.*, 2017]. As this is not the primary focus of this paper, we have used criteria for event length and definition of the start and end of the recession similar to be consistent with previous studies. However, the sensitivity of extraction criteria on parameter estimation is valid consideration and we have added to the paper. We have expressed a and b given the Equation of the falling limb of the hydrograph: “$a=-w/(\tau Q_o^{1/w})$” and “b = (1+w)/w”. Because b is only dependent on w, the individual recession b will be sensitive to the recession extraction for w. For a, recession extraction will affect Q_o and w. However, the offset will still occur which creates the difference between the individual recessions and the point cloud unless w goes to infinity. For Case 1, we changed the overland flow variable between 0, 1, and 2 days. This changed where the recession start was defined and thus Q_0. Given $a=-w/(\tau Q_o^{1/w})$, using overland flow of 0 days the range of *a* values for individual recessions is from 0.5 to 4.8 with a mean of 0.48. When overland flow is defined as 1 day (i.e. the first day of the recession is excluded in parameter estimation) the range of *a* values for individual recessions are from 0.5 to 5.4 with a mean of 0.50, When overland flow is defined as 2 days (i.e. the first two days of the recession is excluded in parameter estimation) the range of *a* values for individual recessions are from 0.5 to 5.6 with a mean of 0.50, For all three overland flow values evaluated, the point cloud *a* was 0.17.This discussion has been added to the synthetic hydrograph results. Regarding the sensitivity of parameter estimation sensitivity, we evaluated how choosing the overland flow duration changed the value of *a* and found that the start of the recession to be relatively insensitive to *a*.

Additionally, we have reworded the information about the minimum recession length to clearly define the minimum recession length before the overland flow cutoff is applied. Regarding the comment about rainfall, we have included a sentence explaining that we did not use rainfall data for extraction criteria because a complete rainfall dataset is not always available for a watershed (while it available for the watershed presented as an example in this study) and no rainfall record was created for the synthetic hydrograph. This allowed our methods for recession extraction to be consistent between the real-watershed example and the synthetic hydrographs.

3. median parameters from individual recession analysis (P03L04): I missed a discussion about seasonal catchment or streamflow behavior in the paper. There are many studies with recession analysis considering seasonal components in a, b, and dQ/dt Q-plots. The authors should at least refer to those studies or give a comment on the issue.

Authors Reply: We agree that a discussion on the literature looking at seasonality of a and b is important to this discussion. In the introduction, we have added a discussion of point cloud analysis that is sub-setting to months or season [*Szilagyi et al.*, 2007; *Thomas et al.*, 2015] and seasonal trends of a and b for individual recessions [*Bart & Hope*, 2014; *D. Dralle et al.*, 2015; *Karlsen et al.*, 2018; *McMillan et al.*, 2011; *Shaw & Riha*, 2012; *Tashie et al.*, 2019].

4. Why synthetic hydrographs (P03L08)? Advantages of this approach should be (shortly) mentioned (earlier than in Sect. 2.2).

Authors Reply: Synthetic hydrographs were chosen for this study because each individual recession can be definitively identified as the characteristics are known which is unrealistic when considering real watersheds. Furthermore, the synthetic hydrographs can be specified to directly compare different hydrological controls without the confounding variables traditionally associated with real watersheds. For these purposes, the specifications of the synthetic hydrographs were chosen to explore the effects of the magnitudes and frequency of recharge events on the recession analysis parameters from collective vs. individual recessions. The justification for using synthetic hydrographs has been added to the methods section 2.1 under the synthetic hydrograph methods.

5. Section 3 is Results, not Methods

Authors Reply: Corrected. Thank you.

6. "The pre-defined theoretical b values for the LE appear to provide poor fits for the point cloud" (P05L17) very important results for all further studies that using LE and pre-defined b's. You should emphasize this (even more)!

Authors Reply: We agree with this comment. While the poor fit of the LE is an important result, it is not new to our study. To give appropriate credit to previous studies that suggested the problems with the lower envelope method and to corroborate our claim, the sentence references have been expanded "… consistent with previous studies that have shown errors associated with the LE method (Rupp and Selker, 2006a)". We have added a sentence in the conclusions that discusses the 4 fitting methods considered and the apparent poor fit of the LE: "The four fitting methods considered were the lower envelope method, central tendency, binning, and individual recessions. Because of the poor apparent fit and problems pointed out from previous studies, the lower envelope and central tendency were not considered in favor of improved methods for binning of collective recessions and the median individual recession."

Additionally, we have added a discussion about the limitations of using a pre-defined value for b to find the LE fit: "A limitation of using a pre-defined value for b for the lower envelope assumes that the watershed responds like a single homogenous Boussinesq hillslope, which isn't known priori for the LE of a watershed composed of multiple heterogeneous hillslopes of unknown b."

7. more explanation on the hydrological functioning of a and b (or give references), like e.g. P07L11, this would make it easier for a broader readership.

Authors Reply: We appreciate this comment and agree that a practical interpretation of recession parameters was missing and should be included. To the introduction, we have included a description of the interpretation of b where a larger value of b indicates a decreasing streamflow decline and a smaller value of b indicated a faster rate of streamflow decline with decreasing streamflow. For a given value of *b*, a larger value of *a* implies a more conductive/permeable basin.

For a large b value, at low discharges the streamflow decline rate is less rapid than at larger discharges. As an extreme an infinitely large b value will appear at a horizontal line on the recession analysis plot, indicating that the streamflow decline rate is zero and the stable streamflow magnitude would be the value where the individual recession crosses the x-axis. In contrast a b value of 0 would appear as a horizontal line on the recession analysis plot, indicating a constant rate of streamflow decline for all streamflows defined by the value at which the individual recession crosses the y-axis.

In the results of the updated manuscript, we have included the explanation of different parameter estimations result in different water management decisions. For the case studies when comparing parameter estimation for the point cloud vs individual recessions, if the point cloud b is smaller than the median individual b, using the point cloud would indicate a faster discharge decline rate than using the individual recessions and thus a more sensitive watershed to climate change.

8. explain in more detail how the synthetic hydrographs are derived (or give references). Why is this way better than using multiple (real world) catchments?

Authors Reply: Synthetic hydrographs are constructed using successive falling limb of the hydrograph following a power law. The three different cases are different in three ways: 1) the distribution of event magnitudes, 2) the distribution of event distribution, 3) the effect of antecedent conditions. Cases 1&3 have log-normally distributed inter-arrival times ($\mu = 2.5$, $\sigma = 1$) and event magnitudes ($\mu = 1$, $\sigma = 1$), compared to Case 2 with uniform event inter-arrival time ($\mu = 450/\tau$), and magnitudes ($\mu = 1$). The time series is based on concatenating successive individual events based on the guidelines for each case (see Table 1). We have also included a description of the superposition of events for Case 2 and 3 following the nomenclature from Figure 2. We have included an expanded version of this explanation of how the synthetic hydrographs were created in methods section 2.1. We have also included a more detailed description on Hydroshare where the time series for the synthetic curves is available.

We chose to use synthetic hydrographs instead of multiple real-world catchments because we were able to isolate specific climatic controls (event magnitudes, frequency, and superposition of events) between cases. As a result, we were able to specifically examine event magnitude, frequency, and the type of superposition of events in order to assess their influences on individual recessions. We can also determine the influence of parameter estimation for individual recessions and the point cloud. With real watersheds, there are many confounding variables that prevent the deconvolution of the climatic controls. We have also commented on the advantage of using synthetic hydrographs compared to real watersheds in the response to Major Comment 4.

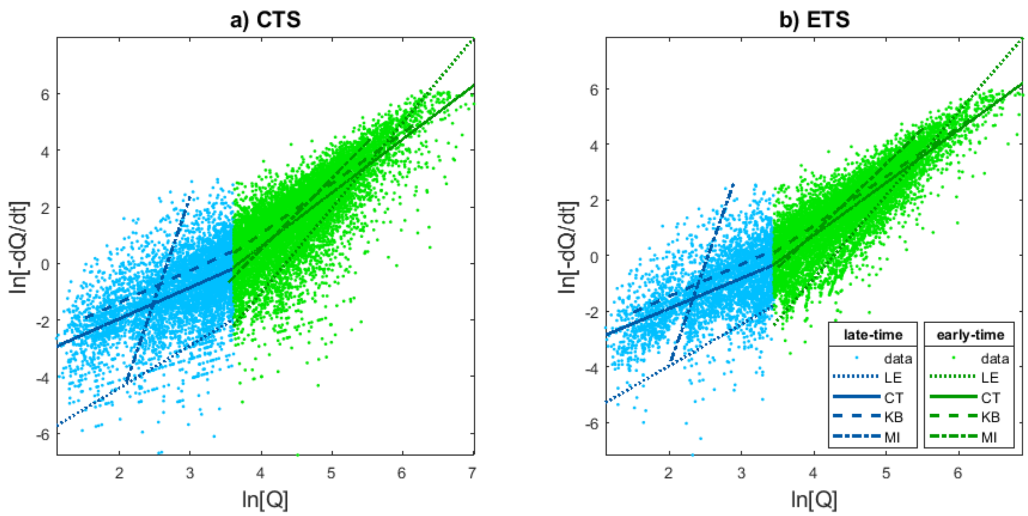
9. How representative is the median b from individual recessions across all Cases 1-3 for the individual recession hydrographs? It might be beneficial to show the distributions of b around the median (e.g. violin plot?)

Authors Reply: Thank you for the comment. We agree that the distributions of b around the median provide valuable information about the variability of watershed responses. We have chosen to represent the distribution of b in the colorbar for each RA plot using percentiles instead of using another graphic such as a violin plot. To increase clarify, we have added more definitive language describing the variability of b in reference to the colorbar of the Figures. For example, for case 2 “the median b represented is 3.25, with the range of individual b between 2.56 and 3.41 (quantiles represented in the colorbar of Figure 5)”

10. I asked myself what is the most sensitive part of the recession analysis presented here? The recession extraction method? The fitting procedure? Are there specific references discussing the different sensitivities? That means the value of the paper could further be improved if the authors give some guidance on how specifically the individual recession segments should be extracted then.

Authors Reply: The reviewer brings up a good point. We acknowledge other authors have looked at the sensitivities of multiple parts of recession analysis including recession extraction [*B. Chen & Krajewski*, 2016; *D. N. Dralle et al.*, 2017], derivative calculation [*Roques et al.*, 2017; *Rupp & Selker*, 2006], and fitting method [*X. Chen et al.*, 2018]. To our knowledge, a comparison between these components to find the relative sensitivity is not published. However, we believe this would be a worthwhile venture to determine which part of recession analysis is the most sensitive for parameter estimation.

We have looked these sensitivities separately. For synthetic recessions, recession parameters are not sensitive to recession extraction methods because w is a constant (see authors reply to major comment 2). Following previous studies, we used common practices for recession extraction criteria. We explored the derivative calculation method’s effects on parameter estimation comparing the constant time step method [*Brutsaert & Nieber*, 1977] and the exponential time step method. [*Roques et al.*, 2017]. While we do see artifacts when using the constant time step, parameter estimation between methods are similar (see Figure and Table below). In contrast, parameter estimation varies greatly between fitting methods. Because parameter estimation appears to be most sensitive to the fitting method, we have used the citation for previous studies looking at recession extraction and the derivative method and focused our analysis on the sensitivity of the fitting method for parameter estimation.



	CTS - *a*		CTS - *b*		ETS - *a*		ETS- *b*	
	early	late	early	late	early	late	early	late
LE	-12.7	-6.1	2.7	0.8	-11.2	-5.8	2.4	0.9
CT	-7.0	-4.1	1.9	1.0	-6.9	-4.2	1.9	1.0
BA	-6.1	-3.7	1.8	1.1	-6.1	-3.9	1.8	1.2
MI	-12.7	-20.3	3.2	7.6	-10	-17.5	2.7	6.4

Minor comments

P01L21 Here the Brutsaert and Nieber and the Kirchner paper are missing.

Authors Reply: Corrected as suggested

P01L24 Add Brutsaert and Nieber, 1977 as a first fundamental paper using dQ/dt-Q.

Authors Reply: Corrected as suggested

P02L03-07 Better change the two sentences: first collective recession analysis remains common, then the recent criticism.

Authors Reply: Corrected as suggested

P02L10 Lower envelope has not been introduced yet.

Authors Reply: Wording clarified- LE introduced P02L08 and wording changed on P02L10

P02L20/21 Explain shorty what a greater b means in terms of recession behavior.

Authors Reply: Done- P02L21-23

P03L11 Last sentence of section 1 is rather a result or a conclusion, but can be rewritten to a hypothesis or research question.

Authors Reply: We have rewritten this sentence as a research objective.

P03L14 I would change the order; first the definition of hydrographs then the parameter estimation methods (which needs the hydrographs to be applied).

Authors Reply: Corrected as suggested

P03L24 Would be helpful to give key references here for the four fitting methods and to state if the original procedures from the references are used or modified.

Authors Reply: Corrected as suggested. For consistency, references have been added in the methods that were first mentioned in the introduction.

P03L27 Why 5% (and not 10%), is 5% common?

Authors Reply: We have added a citation to this sentence with other authors who have used 5%. While Mendoza et. al. (2003) uses 10% and Vannier et. al. (2014) uses 2%, using a quantile threshold of 5% appears to be the most prevalent in the literature.

P06L18 Last paragraph of section 3.2 belongs rather to the methods than to the results section. At least, a reference in the methods section referring to this result should be given.

Authors Reply: Corrected as suggested

P08L21: "sum of the squares”, I don’t get this.

Authors Reply: Unclear wording removed

Technical comments

P01L13 “based on dQ/dt-Q-recession analysis”

Authors Reply: Corrected as suggested

P02L01 why “primary”?

Authors Reply: We have removed this wording.

P02L14: two times Kirchner reference, remove one.

Authors Reply: Corrected as suggested

P02L24 “significantly”? sound like it was statistically proven?

Authors Reply: Thank you for this comment. This qualifier has been removed to avoid a misleading statement.

P03L05 “Being able to. . . vulnerability studies” - the sentence is not well connected here, move up?

Authors Reply: We have reworded this sentence and relocated to increase flow.

P03L22 "theatrical"?

Authors Reply: Corrected as suggested.

P08L22 to understand the underlying hydrology

Authors Reply: Corrected as suggested.

P08L23 Sentence is a repetition of the last sentence of the paragraph before sentence removed

Authors Reply: We have removed this sentence to reduce repetition.