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Interactive comment on "Freshwater resources under success and failure of the Paris climate agreement" *by* Jens Heinke et al.

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We wish to thank the anonymous reviewer for her/his comprehensive and constructive comments. Below, we provide detailed responses and propose changes in the manuscript.

Comment: Although I am not a water manager or decision maker, I do not see that the information provided is particularly actionable. The regions are quite large. Can the authors provide a subset of the most striking examples of sub-regions under population and hydrologic change stress (i.e., map the areas of Table 1 for each degree warming?).

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Response: The main objective of the paper is to inform the climate mitigation discussion with an emphasis on the implications of success and failure of the Paris climate agreement. The focus is therefore on temperature levels at which transgression of critical thresholds may occur as well as on the number of people affected at different temperature levels. This kind of information may not be particularly actionable for water managers, but it is not the paper's intention to provide that. In this light, the table with regionally affected population merely serves a breakdown of global aggregated affected population presented before, to highlight that: (i) affected population is unevenly distributed around the globe; and (ii) the extent to which numbers of affected population increase with temperature also differs greatly across regions. A further breakdown into smaller sub-regions would bear the risk of obscuring these massages by adding too much detailed information. Also, the second aspect would be difficult to see in a set of maps.
Changes in manuscript: There is certainly potential to sharpen the key messages in the paper (not only those related to Table 1) and to state the objective of the paper more clearly. We will address this in the revised manuscript.

Comment: The authors also do not discuss regional uncertainty in the GCMs or SSPs. For example, Fig. S7 shows (white) areas where there is disagreement among models and conversely, agreement among models. I would think at least the model spread (as a surrogate for projection uncertainty) should be discussed in-hand with the water stress projections.
Response: In this paper, GCM uncertainty is addressed by analysing only impacts that are 'more likely than not'. This is also the case for the regional results in Table 1. Analysing model spread represents an alternative way of dealing with projection uncertainty and has been extensively applied in existing literature. We consider the approach taken in this paper to be more suitable with the intended objective to inform the climate mitigation discussion. The model spread shown in Fig. S7 only serves as a basis for comparison of our projections with existing literature, namely Schewe et

al., 2014. The impact of population scenario uncertainty has been taken into account explicitly by analysing results for all five SSP population scenarios. However, since our findings show that most aspects of population exposure to severe hydrological change do not vary much across population scenarios, we have decided to focus on the medium scenario SSP2 in the main paper and show detailed results for all other SSPs in the SI only.
Changes in manuscript: We see that there are a few places in the manuscript where the reference to the SI material can be improved. We will address this in the revised manuscript.

Comment: I also misunderstand the statistics for "ANY" hydrologic changes (e.g., Fig 2 and throughout). Take the Indian subcontinent, for example, which is colored in panel (d) but not for (a-c). How can the "ANY" affected area exceed the sum of the area for the 3 metrics of severe change?
Response: Fig. 2d shows the temperature for each pixel, where severe hydrological change of any of the three types occurs in 10 out of 19 GCMs. For example, this could be a combination of 5 GCMs showing transgression in MAD and 6 other GCM showing transgression in ND, which booth would not show up in the individual maps for these metrics.
Changes in manuscript: We will improve the explanation of the Fig. 2d and the ANY metric.

Comment: The "majority", "more likely than not" and other terminology was introduced but not consistently or clearly applied throughout the paper.
Changes in manuscript: We will revise manuscript to assure consistent use of terminology.

Comment: Abstract: the fact that MAD, ND, and Q10 are used to quantify variability *needs explicit mention.*

Response: Although we regard the consideration of variability related hydrological change as an important contribution, we do not think it needs to be emphasized in the abstract. Instead, we believe the paper will benefit from a stronger alignment along the term 'severe hydrological change', which summarizes severe changes in aspects that are related to variability (ND and Q10) and aspects that are not (MAD).

Changes in manuscript: Rewrite to assure consistent use of the term 'severe hydrological change' throughout the paper. In particular, we will add a short definition of 'severe hydrological change' in the abstract and a more detailed motivation in the introduction.

Comment: Ln9 suggest something closer to the following: "by water scarcity. [Simultaneously, global warming is shifting the seasonality and overall quantity of available water. This study estimates the separate and joint effects of population growth and hydroclimate change on global water resources for a range of warming scenarios, ranging from +1.5- 5C. Hydroclimate change is quantified through three metrics: mean annual discharge, number of drought months, and magnitude of the ten-year return flood event. . . .and evaluates how climate [change] mitigation. . .hydrological change, as well as the severity of the water scarcity. The results show that without climate [change] mitigation. . ."

Response: We much appreciate these improvements to the abstract. However, the main focus of our study is on severe hydrological change related to climate change and not on water crowding/scarcity. The latter only serves the purpose to highlight where severe hydrological change may matter the most and be of societal relevance. We see that the abstract does not make this clear in the best possible way and we will revise the abstract to improve this aspect.

Changes in manuscript: Revise abstract to improve clearness of study objectives and elements.

Comment: Pg2ln1-5 there should be discussion of changing precipitation phase (snow vs rain), earlier springs, longer growing seasons, and glacial melt (Himalayas).
Response: We agree that the paper would benefit from an elaboration of what we mean by 'changing the hydrological conditions' here.
Changes in manuscript: Include a sentence/section that lists examples of changing hydrological conditions due to climate change.

Comment: Pg2ln23 it is unclear how the current approach addresses "changes in variability"
Response: We agree that "changes in variability" is a very broad term and that this sentence requires refinement to express more clearly what is missing in existing analyses and what will be address in this study.
Changes in manuscript: Rephrase sentence/section.

Comment: Ph2ln27 the number of drought months does not tell us about the severity of the drought. And multi-year droughts are not identified because every year is treated independently.
Response: During preparation of the paper we have experimented with various metrics of drought severity but found the outcomes to be very inconsistent and highly dependent on the chosen metric. We therefore decided to use the number of drought months as a metric for changes in droughts, which is simpler and more transparent. ND as calculated here does in fact cover multi-year droughts as the CDM method is applied to the entire continuous time series.
Changes in manuscript: Explicitly mention that ND is able to capture multi-annual droughts.

Comment: Pg3ln14 suggest [0.5 x 0.5 degree grid cell]
Changes in manuscript: Apply proposed changes.

Comment: Pg3ln22-23 where does temperature come from? In cases for which GPCC and CRU precipitation are both available, which one is used, or how are the two estimates merged? These datasets revert to climatology in months for which observations are not available. So, the inter-annual variability of the random sample will be less than actual unless these years are filtered.
Response: There is a typo in this line, it should read: "[..], time series are based on temperature and cloud cover from CRU TS3.1 [. . .]." For precipitation, only GPCC is used. The problem that datasets revert to climatology in months where observations are missing, is primarily an issue in the first half of the 20th century in the CRU dataset. For the construction of the reference time series the period 1961 – 2009 was used, and it should therefore be largely unaffected by this problem. In addition, the months instances where the climatology was used are difficult to identify and their removal would introduce artifacts in the reference time series (only full years and global fields were resampled to retain the temporal and spatial autocorrelation of climate data).
Changes in manuscript: Correct typo.

Comment: Pg3ln24 suggest "[random] resampling [with replacement]"
Changes in manuscript: Apply proposed changes.

Comment: Pg3ln27 what are the inputs and parameters for LPJmL?
Response: The method section provides detailed information about the climate inputs used to drive LPJmL in this study. A paper including a full model description including all standard input data and parameters has just been published (Schaphoff, von Bloh, et al., 2018), along with a comprehensive model validation paper (Schaphoff, Forkel, et al., 2018). At the time of submission of the present manuscript these papers were still pending final publication. Hence, only the corresponding discussion papers of both these papers could be referenced. These refences will be updated in the revised

version of the present manuscript.
Changes in manuscript: Update references of model documentation and validation.

Comment: Pg5ln7 it should be noted that in practice the seasonality of the MAD shortfall matters, since the reservoirs (and rivers) are managed for alternative purposes including flood management and hydroelectric power generation
Response: Decrease in MAD (mean annual discharge over 30 years) is a metric for the decline in long-term average water availability. It lacks any information of seasonality or interannual variation, which is the very reason why we have complemented it with metrics capturing changes in droughts and floods.
Changes in manuscript: None.

Comment: Pg5ln16 is this "river discharge" or "grid cell runoff". There is no mention of a routing scheme. Is the CDM approach most needed because the analysis is on a grid-by-grid basis?
Response: It is river discharge. The routing scheme is in not mentioned, indeed. The CDM approach is needed to identify droughts in ephemeral rivers.
Changes in manuscript: Add description of routing scheme.

Comment: Pg5ln26 why not just use the standardized precipitation index-6months (SPI-6)?
Response: SPI and related indices are used to detect meteorological drought whereas the focus in this paper is on hydrological drought.
Changes in manuscript: None.

Comment: Pg6ln14 large floods can be important "drought busters". What is the logic for penalizing Q10 floods in a water scarcity context? Could the authors provide further

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justification for the 30% threshold? What is the relative frequency shift? i.e., Q10 plus 30% is what return flood on-average for each region?
Response: Because the return time of large floods (with a typical return time of 100 years or more) is difficult to estimate from a 30-year time series, we use an increase in Q10 as a proxy for an increase in such large floods. For typical extreme value distributions, the increase in Q100 will always be lower than the increase in Q10, but the exact relationship is not known and depends on the exact shape of the extreme value distribution. Therefore, the 30 % threshold is inherently difficult to justify. What can be done, and that is indeed missing here, is to give a range of possible increases in Q100 and Q1000 that correspond to a 30 % increase in Q10 based on a range of typical shapes (parameter combinations) of extreme value distributions. This would then also make clear that the focus of this metric is on large floods rather than Q10 itself.
Changes in manuscript: Rephrase and clarify. Add typical ranges for increases in magnitude (and/or decrease in return time) of Q100 and Q1000 corresponding to a 30% increase in Q10.

Comment: Pg6ln19 the authors have omitted a section introducing SSP scenarios
Response: SSP storylines are extensively covered in existing literature precise knowledge about these storylines is not needed for the interpretation of results in this paper. Nevertheless, mentioning at least the scenario names is certainly useful.
Changes in manuscript: Add section with short SSP scenario description.

Comment: Pg7lns11 what are the "basins" that were used. Can these be illustrated?
Response: River basins are defined by the drainage network also used for river routing in the model. However, the description of the routing network is missing (see comment above) and will be added in the revision.
Changes in manuscript: Add description of routing network.

Comment: Pg8ln4-5 it would be useful for the authors to provide figures that better illustrate the relative/shared contribution of both pathways named here.
Response: The focus of this paper is on population exposure to severe hydrological change due to global warming. The water crowding analysis merely serves as a means to estimate where theses changes may matter the most. We do not think that knowing how much of future water stressed population is caused by each of the two pathways is relevant in this context. In particular, as the amount of information is quite large (5 SSPs times 5 crowding classes). In addition, it may not be so easy to disentangle the two cases as population will often continue to grow after a pixel has tipped into water stress or scarcity.
Changes in manuscript: None.

Comment: Pg8ln8 define "substantial"
Response: Another (and probably better) word that would fit here is 'considerable'. While we agree that both terms are rather vague, a more precise wording is not required at this point. Detailed information on population affected by severe hydrological change at different levels of global warming is provided in the remainder of this section.
Changes in manuscript: None.

Comment: Pg8ln9 what is "severe"
Response: Thresholds for what consist a severe change in MAD, ND, and Q10 are defined and motivated in the method section. However, we see that it is not entirely clear that these thresholds are referred to here.
Changes in manuscript: Add clarification that 'severe change' relates to the thresholds defined in the methods. Name them explicitly here again.

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Comment: Pg8lns17-19 are these statistics from a table or figure or not shown? Is it 108 million fewer or total impacted? 319 million fewer or total? 15 million fewer or total? Unclear if "these figures" are total affected or differences from 5C numbers is prior paragraph.
Response: All numbers mentioned in this section are displayed in Fig. 2. All three numbers mentioned by the reviewer are totals not differences. Changes in manuscript: Clarify that these are totals.

Comment: Pg8lns16-30 is there no feedback between the population scenario and water availability? Will population continue to grow as projected despite severe shortages of water?
Response: Population scenarios and their spatial disaggregation are given by the SSP storylines. Thus, potential deviations from the SPP projections which 'in reality' would be the result following impacts from water scarcity, are not captured in this study, nor are they in any other such study, to our knowledge. It is worth mentioning that under extreme scarcity population growth could not be sustained or that a shift towards non-conventional water resources (e.g., desalination) may occur. Changes in manuscript: Add a comment on that in methods or discussion.

Comment: Pg9ln2 "water supply systems" statement is vague and should be qualified by references
Changes in manuscript: Rephrase and/or qualify with references.

Comment: Pg9ln9 where regionally are these 2.99 billion people concentrated?
Response: This can be seen in the first column of Table 1 but is not explicitly mentioned in the text since the focus of the paper is on severe hydrological change and not on water crowding. However, we will revise this section to give the regional results more weight and may include a reference to regional water crowding numbers.

Changes in manuscript: Rephrase/clarify and add reference if required.

Comment: Pg9ln11 where geographically is this change in high crowding projected?
Response: This seems to be a misunderstanding: water crowding is a static overlay in our analysis, calculated from river discharge under contemporary climate conditions and future population patterns (here SSP2). We will make sure to make this clearer in the revised manuscript. The regional distribution of population experiencing water scarcity and severe hydrological change is given in Table 1 and discussed in the main text.
Changes in manuscript: Rephrase/clarify.

Comment: Pg9ln13 "occur in places", please provide examples.
Response: This not as easy as it seems. Water crowding often occurs in places of small spatial extent (a few grid cells) but high population density (i.e., cities). We do not think that the scale of analysis (global model, pattern scaled climate scenarios, 0.5 degree resolution) allows to report results at the scale of cities. Regional examples are given in Table 1 and are discussed in the text.
Changes in manuscript: None.

Comment: Pg9ln18 I misunderstand. How is ANY (1.94billion) larger than the sum of MAS, ND, and Q10?
Response: This is because in the ANY category, population is in at least 10 out of 19 GCM exposed to a severe hydrological of any kind. Thus, all combinations of severe for MAD, ND, and Q10 are possible here. For example, a transgression of MAD in 5 GCMs and a transgression of ND in 6 other GCM, would mean a pixel and its population is considered in the ANY category but neither in the MAD nor the ND category. While we have tried to provide a definition of ANY in the paper (p8ln25-28), we acknowledge that correct understanding is crucial and deserves more space.

Changes in manuscript: Improve explanation of ANY category.

Comment: Pg9ln21 it would be instructive to see the regional distribution of the projected benefit of the Paris agreement
Response: This is shown in Table 1 and described in the following section.
Changes in manuscript: None

Comment: Pg9ln22 intended reference to "remaining number of people affected by severe hydrological change" is unclear.
Changes in manuscript: Rephrase and clarify.

Comment: Pg9ln26 clarify here if "11% of total population" is of global affected population (274mil) or LAM or MEA population
Changes in manuscript: Rephrase and clarify.

Comment: Pg9ln26 is this "another 29% [of the affected global population] live in SAS and SSA, although they locally comprise only 2% of the population"?
Response: This is correct.
Changes in manuscript: Apply proposed change.

Comment: Pg9ln28 "since substantial societal and economic efforts". Please clarify or add a reference.
Changes in manuscript: Rephrase/clarify and add reference if required.

Comment: Pg9ln31-32 "reduce the costs" this may not always hold. Depending on the region and the solution, the infrastructure investment to serve 5% may be just as

expensive as serving 10%.
Response: Under conditions of unconstrained water availability it is conceivable that strong economies of scale allow to increase societal water supply at little extra cost. But it is unlikely that this cost is zero. However, this is not what the respective statement in the manuscript refers to. The underlying assumption here is that severe hydrological change will increase the cost for maintaining or increasing societal water supply (see Methods). The smaller the number of people affected by severe hydrological change the smaller these costs. This does not mean that achieving water-related SDGs will come at no cost, it just means that avoiding severe hydrological change will not make them more expensive.
Changes in manuscript: Rephrase and clarify.

Comment: Pg10ln3 "one quarter of the total population" I am a bit confused with this statistic following the 11% figure cited in the prior paragraph.
Response: The first figure (11 %) is the percentage of people affected at 2 °C. "One quarter of total population" refers to the percentage of people affected at 2.5 °C.
Changes in manuscript: None.

Comment: Pg10ln14 a version of Fig S6 should be included in the main article.
Response: Table 1 is in fact a full representation of the panel SSP2/ANY in Fig. S6. We do not think that detailed results for MAD, ND, and Q10 or additional SSPs are required in the main paper. Changes in manuscript: None.

Comment: Pg11ln16 the meaning/intent of "disproportionally strong" is unclear
Response: It means that severe hydrological change tends to occur in places affected by water scarcity.
Changes in manuscript: Rephrase and clarify.

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Comment: Pg11ln19 suggest "affect populations [already coping with water scarcity]. Since the specific affected populations have not been identified or discussed, I do not believe a statement about "room for further adaptation" can be supported here.
Changes in manuscript: Apply proposed change.

Comment: Pg11ln22 the phrase "more likely than not" should be italicized and applied more methodically throughout where appropriate.
Changes in manuscript: Check and improve consistent use of 'more likely than not' and related terms throughout the manuscript.

Comment: Pg11ln22-23 suggest "hydrological change. [Of those affected, 1.9 billion (21.2% of global population) would have. . ."
Changes in manuscript: Apply proposed change.

Comment: Pg11ln23 "limited capacity to adapt". Again, I do not believe the study supports statements about barrier to adaptation. It is unclear that population pressure [always] limits capacity to adapt.
Response: The assumed relationship between population pressure and capacity to adapt is indeed never justified or explained in the paper.
Changes in manuscript: Clarify with references how population pressure relates to capacity to adapt or remove statement.

Comment: Pg11ln30 separate statistics should be cited for Latin America and Middle East and North Africa regions
Changes in manuscript: Apply proposed change.

Comment: Pg12ln1-2 Is this statement sill in reference to LA and MEA or globally,

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in-general?
Response: This refers to LAM and MEA.
Changes in manuscript: Rephrase and clarify.

Comment: Fig1 the flow unit should be defined in the caption. Why is SSP3 so different in terms of total population growth? I'd personally prefer a figure with panels for each region with pop. Growth and % in each water class.
Response: Yes, flow units should be defined in the caption or the figure itself. Population growth in the different scenarios is determined by the storyline assigned to these scenarios. SSP3 is an extreme scenario in many aspects of its storyline so it is no surprise that it shows the most extreme population increase. However, the reasons for the differences among population scenarios are not relevant for the understanding of this paper.
Changes in manuscript: Add definition of flow units in the caption or the figure.

Comment: Fig 2. The specific thresholds that define "critical", i.e. 20% decrease in MAD, 50% increase in ND, and 30% increase in Q10 should be noted here.
Changes in manuscript: Add definition of severe hydrological change.

Comment: Fig3. Clarify in the caption that this data corresponds with Fig.2. Why is the population affected by the two classes unvarying? It appears to be 3billion for all cases for <1000 p/fu. Why not just limit the x-axis to 70% for readability? Big takeaways- droughts are impacted at all warming levels, MAD above 2C, and Q10 above 3C?
Response: Water crowding is calculated for climate representing contemporary conditions and is therefore independent of climate change. Extending the x-axis to 100 % has the benefit of preserving the correct proportion of coloured areas (affected population) to total plot area (total population).
Changes in manuscript: None.

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Comment: Table 1. What is the scale factor for the population? The map of the regions delineated should be included in the main paper. Does the 33% of global population correspond to the "any" category in Fig 2d? Does the 21.6% of global population affected at +5C correspond with the "any" category in Fig 3d? Where would the 65% from Fig 3d fall in this table, if there was an additional section? Clarify that all percentages are provided as a percentage of total global population.
Response: Population is given in million. We do not think that a map of regions is necessarily required in the main paper since the region names are quite common and can be readily understood. The 33.3% correspond to the total number of people affected by water scarcity (>1000 p/fu) in Fig. 1. Yes, 21.6 % corresponds to the affected population at 5 °C warming in the ANY category in Fig 3d. The 65 % in Fig. 3d are the percentage of people under water scarcity affected by severe hydrological change (1940 out of 2988 million). All percentages are given are percentages of population in the spatial unit denoted in the first column (10 regions and 1 world).
Changes in manuscript: Mention that population numbers are in million and that percentages refer to region/world totals.

Comment: Fig S1 Most differences appear in Middle East, China, South Asia, and North Africa. The discussion and supporting figures could do better to highlight this finding.
Changes in manuscript: Improve reference to supporting material in main text.

Comment: Fig S2 why does the SSP2 scenario no match what is shown in Fig.3?
Response: Fig. S2 matches Fig. 2.
Changes in manuscript: None.

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Comment: Fig S3 "water [crowding]"
Changes in manuscript: Apply proposed change.

Comment: Fig S4 "water [crowding]"
Changes in manuscript: Apply proposed change.

Comment: Fig5 this belongs in the main article.
Response: We do not think that a map of regions (Fig. S5) is necessarily required in the main paper since the region names are quite common and can be readily understood.
Changes in manuscript: None.

Comment: Fig S6 consider a version of this in the main article. Perhaps 10 panels covering each region?
Response: We plan to give the regional results more room in the revised manuscript. Perhaps with an additional figure similar to the one proposed.
Changes in manuscript: Give more room to regional results, add figure if appropriate.

Comment: FIgS7 Why not include this plot and parallel plots for ND and Q10 in the main article?
Response: This Fig. S7 is a reproduction of a figure in another paper (Schewe et al., 2014) based on our own simulation results. Its sole purpose is to demonstrate how our simulation results relate to the results from a more comprehensive model ensemble in that paper. The way we analyse our results in the main paper, in particular the way we deal with uncertainty (by reporting only results that are more likely than not), differs fundamentally and is not compatible with this kind of arrangement. Thus, we think Fig. S7 is adequately placed in the SI.

Changes in manuscript: None.

References

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