We thank all referees for their useful comments which helped us to improve the paper and to submit a new improved version of the manuscript. We answer below to each comment point by point.

Referee #1

General Comment

This is a very well-written review paper on the impact of climate change on runoff in West Africa. The authors show future runoff change in West Africa is very uncertain, by investigating 19 published papers (i.g. multiple GC, multiple scenario, multiple hydrological models). Because of such a large uncertainty, it is dangerous to judge a future trend of runoff in West Africa from the results of one or few studies. Therefore, I think the authors' work is useful. I recommend the paper to be published in HESS after minor revision.

Thank you.

Specific Comments

P2483, Title: I think this study is on "runoff" but not "river discharge". River discharge is a flux of water at a specific point in river channel. Therefore, I think the term "river discharge" may lead to misunderstanding of the results. For example in Figure 4b, "river discharge" of "the lower Niger" should be the summation of runoff in the "upper, middle and lower Niger", while "runoff" in "the lower Niger" only accounts for the runoff from "the lower Niger" area. I recommend the authors to change the word in the title.

We agree with reviewer #1 and we therefore changed the title to: "Climate change impacts on river runoff in West Africa: a review"

P2484, L10: "PET" Please don't use an abbreviation (PET) without mentioning it's full description in the abstract.

Corrections made as recommended by referee #1

P2484, L15: "an urgent need for integrated studies that quantify the potential effects of these processes on water resources in West Africa." Integrated studies are off course important, however improvement of climate model's accuracy is also essential given that the runoff change is mostly decided by projected future rainfall.

We agree on this point that we added in the manuscript.

P2489, L22: "Since such scenarios are within the range of potential evolutions simulated by the GCMs, we decided to include them in the database." Even though the scenario is within the range of GCM projections, inclusion of "okpara and Perumal 2009) may introduce a bias in the results because runoff change is dominated by rainfall change. I think if the scenario (-5% rainfall) does not have any scientific basis, it should be removed from the database.

Okpara and Perumal (2009) are indeed not using climate data based on GCMs or RCMs, but anomalies scenarios. We focus here on the scenario +2C/-5% of rainfall that is, as underlined by the last IPCC report (WG I, chapter 14) very close to the median future climate (temperature: +1.9 C, rainfall +3%, ranging from -8% to +8%) according to 42 climate models, in 2100 and for scenario RCP 4.5 over West Africa. We therefore believe that this approach makes sense and should be included in the database. Moreover, we underline that the delta methodology (or anomalies scenarios) is a common methodology, used for example in Sultan et al., 2013 or in the international project AgMIP (Agricultural Model comparison and improvement project) as long as the temperature and rainfall changes are within a reasonable range, defined by the climate models.

P2491, L6: “2 -CO2” It’s better to clearly write “doubling CO2”

Corrections made as recommended by referee #1

P2492, L2: “we clustered river basins” If possible, please draw the boundaries of these clusters in Figure 1a.

Changes made as recommended by referee #1

Figure 1b: The colors for the Niger River are not clear. I recommend to change the colors.
Figure 4(b) It’s better to write the definition of “Niger” in the caption (i.e. no description on upstream or downstream in the original paper in the database). It’s quite confusing.

We changed the colors and the definition of “Niger” following referee #1 suggestions

Figure 7 Please describe which colors (red or green) represents which signal (decrease or increase).

We added “increase” and “decrease” to figure 7

Referee #2

General Observations:

The paper provides an in-depth analysis of the available studies related to the effect of climate change on the runoff behavior of the Sahelian, Sudano-Sahelian and Sudanian rivers in West Africa. The effect of changes in land use, water consumption and higher carbon concentrations on the hydrograph of the rivers in this region of the African continent, due to the limited number of available studies focusing hereon, is less developed. Although future predictions suggest an increase in precipitation (referred in this paper and elsewhere as the main factor affecting runoff) in the study area, the results evidence contrasting findings and therefore a lack of a clear tendency for most of the rivers or subzones. The manuscript not only stresses the need to assess the uncertainty bounds on the predictions of future scenarios, particular in view of decision-making, but also provides where possible uncertainty ranges.
The paper is well written and concrete; the methodology is simple and easy to follow.

Thank you.

However, I would suggest the following minor changes before final publishing in order to improve the comprehension of the reading:

1.Page 2488, Line 23: Consider adding an explanation (after Section 2.3), including some references, on the type of scenarios considered in the database, at least the most common ones, their evolution and considerations (for instance, from the IPCC92 type scenarios until the more recent RCP scenarios). Besides it would be good to include a comparison of two or more common contrasting scenarios like A1F (or A2) vs. B1 (which are we believe are available in the authors database). The better understanding of implications/considerations of each scenario is a key to understand discordances (lack of a clear trend, or uncertainty) between results of different studies. Different climate change scenarios can yield large and contrasting differences in the estimated impact on discharges (e.g., Arnell and Reynard, 1996).

We modified this section in order to provide more information about GHG emission scenarios:

"Many different types of scenarios are available and are clustered in three main groups, that were created in chronological order and used for the different IPCC reports: the early IS92 (Leggett et al., 1992) including for example scenario IS92a or IS92c, the SRES (Special Report on Emission Scenario, see Nakicenovic and Swart (2000) for a description) with for example scenarios A1B, A2 or B1, and the RCPs (Representative Concentration Pathways, Moss et al. (2010)) used in the fifth IPCC report (e.g. RCP 2.6, RCP 4.5, RCP 8.5). Each group constitutes a range of possible emission scenarios, from low (e.g. for the SRES, scenario B1 that leads in 2100 to an average warming of +1.9°C) to high levels of GHG emissions (e.g., A2, that leads to +3.1°C by 2100, see Meehl et al. (2007))"

2. Page 2489, Lines 14-18.: This affirmation is not completely correct. If correctly understood the studies to which the authors refer are primarily based on the SRES and the IS92-type (IPCC 92) GHG scenarios. Just one research paper, the database, is using the lastly developed RCP scenario.

Referee #2 is right, we added a reference about IS92 scenarios (see point number 1).

Specific Comments:

1. Page 2485, Line 8:
"and especially in rainfall, plays a significant role in flow variation in WA". Suggest to delete "WA", because the statement is true not only for WA, but many other regions.

We deleted "WA" in the sentence

2. Page 2485, Line 9: This sentence needs a reference (e.g., IPCC report or Wuebbles and Ciuro, 2013).

We added the Wuebbles and Ciuro (2013) reference

3. Page 2485, Lines 18-19: Why not referring to one of the recent and widely known IPCC evaluations of climate change, which contains trends of some hydrological parameters at regional scales?

The point is that the AR4 and AR5 do not provide a lot of information about the impact of future climate changes on runoff in West Africa specifically, but more for Africa as a whole, for East Africa or for <u>past</u> changes in WA. For example, in the AR5 (WG II, chapter 22), the only results quoted for the Niger River are for a tributary (the Bani).

4. Page 2486, Line 20:
"some rivers in WA can be very large",…are not all of the rivers considered in the study large?

We mean here that not all studied rivers are very large like the Niger or the Nile River. Even if the Sassandra is not a small river, its size is still much below the Niger's.

5. Page 2487, Lines 19-20: Are the ranges over a specific period of time, for example a year, and for which scenario? For instance: the average annual range specified in the mentioned document is between 1.8 and 4.7C for the A1B scenario using a set of 21 global models. The authors could also specify the range for future evolution of precipitation mentioned in the same report (from -9% to 13%). Instead referring to the ranges cited in Christensen et al. (2007), why not mentioning the new ranges mentioned in the last IPCC 2013 report?

Point well taken. We updated the projections following results of the last IPCC report (WG I, chapter 14), that are, according to 42 climate models and scenario RCP 4.5 and for 2100:

- ***Temperature: from +1°C to +3.2°C***
- ***Rainfall: from -8% to +8%***

6. Page 2488, Lines 19-22: Are the rising CO_2 concentrations not inherently considered in the climate change scenarios? What you are referring to in this paragraph is the effect of rising CO_2 on PET and leaf area index; which on its turn indirectly might affect runoff. Would it more appropriate to rename this paragraph to "Carbon effect on plant water use", as used in Section 3.4.

We followed referee #2 advice and renamed this section

7. Page 2489, Line 8:
"19 peer-reviewed papers, Ph.D thesis or"...Do you mean 1 Ph.D thesis or more than 1 Ph.D theses?

We mean: 16 papers, 1 PhD thesis and 2 official reports. Changes were made in the text.

8. Page 2489, Lines 23 and 26: Might be appropriate for the readers not familiar with the topic to define the acronyms RCM (Regional Climate Model) and GCM (General Circulation Model).
9. Page 2493, Line 1:
All these results show that futures studies.... "futures"should be replaced by "future".

Corrections made as recommended by referee #2

10. Page 2493, Section 3.2. The fact that precipitation is the major driver for changing trends in discharge, compared to the effect of PET or temperature, should not come as a surprise as stated by Dai et al. (2009) and Gerten et al. (2008). Although the fitting of the discharge values with rainfall is rather moderate (R=0.49), most likely the consequence of the diversity in methodologies, hydrological models and scenarios used in the different studies, the conclusion that rainfall is the main driver is still an acceptable conclusion.

We agree with referee #2 on the fact that this result is not a surprise, as we precise in the manuscript: "These results are in accordance with earlier findings in the literature which underline the major role played by rainfall on future runoff changes (Kundzewicz et al., 2007)". However, we believed it was still interesting to study this point (i) considering many studies and (ii) focusing on West Africa.
Moreover, we did not quote Dai et al. (2009) and Gerten et al. (2008) as they are dealing with past streamflows and as the range of future temperature increase is much larger than past changes.

11. Page 2498, Line 17: Here, and elsewhere in the text, change the reference of the discussion Paper of Aich et al. (2013) to the final revised paper (Aich et al., 2014).
12. Page 2493, Line 24: (e.g., Guimbertau et al., 2013) instead of (Guimbertau et al., 2013).

Corrections made as recommended by referee #2

13. Page 2494, Line 23: Did you mean...the trend for higher return periods (or more extreme floods) is not consistent

We modified this phrase:
"whereas the trend for higher return periods floods (i.e. more extreme) is not consistent"

14. Page 2494, Line 25: Probably you did mean "Fig. 1b" instead of "Fig. 1a".

Indeed. Thanks.

15. Page 2496, Lines 24-26: For sure changes in the behavior of runoff is the combined result of changes in rainfall, land use, water consumption and carbon concentrations. Given the lack of knowledge of the mutual interactions, studies that analyze the integrated effect of the different drivers are needed. Should here or somewhere else in the manuscript (e.g., the Conclusions) not be given a hint in what direction such studies should be conducted? Most of the time researchers study the combined effect of climate change and CO2 enrichment, or climate and land use change, or climate and water consumption change on the runoff behavior. Can those studies [such as Murray et al. (2012); Zhu et al. (2011); Liu et al. (2012); Cornelissen et al. (2013); just to name a few] be indicative how the interaction between the different drivers ought to be analyzed?

We agree with the reviewer. Studies typically have focused on the effects of climate change only or include just one of the additional drivers and evaluate its marginal impact. Instead an integrated approach (either within one model or through two-way coupling of different models) is needed that simultaneously includes the driving processes that link climate, carbon, water, and terrestrial vegetation dynamics. We have made this clearer in the Conclusions section and furthermore refer to the paper of Gerten (2013), who analyses the effects of and interactions between vegetation, water, climate and human activities with the process-based LPJmL global biosphere model.

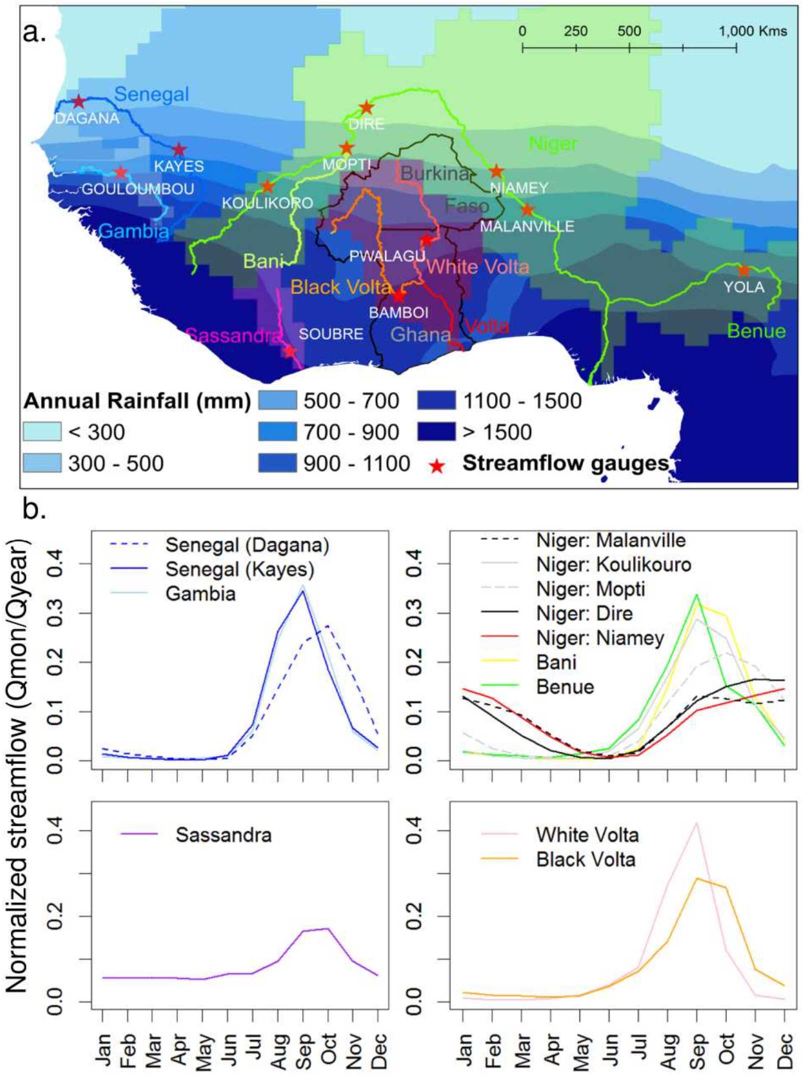
"There is also an urgent need to take into account the other factors influencing runoff, especially water and land use changes, in order to get a more comprehensive assessment and to guide the elaboration of sound adaptation strategies. This can be achieved through the use of integrated process-based models that simultaneously include the driving processes that link climate, carbon, water and terrestrial vegetation dynamics (Gerten (2013); Guimberteau et al. (2014))."

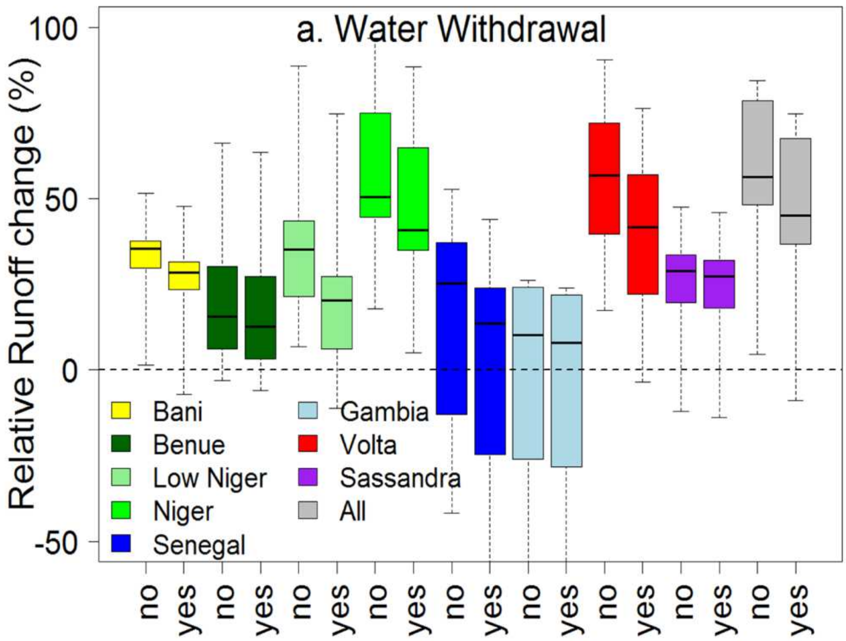
16. The abbreviation WA is used 38 times in the text (at least if correctly counted). Wonder if this abbreviation cannot be deleted in a number of phrases!

We deleted "WA" when possible and replaced it by "West Africa" in the conclusion to be more understandable.

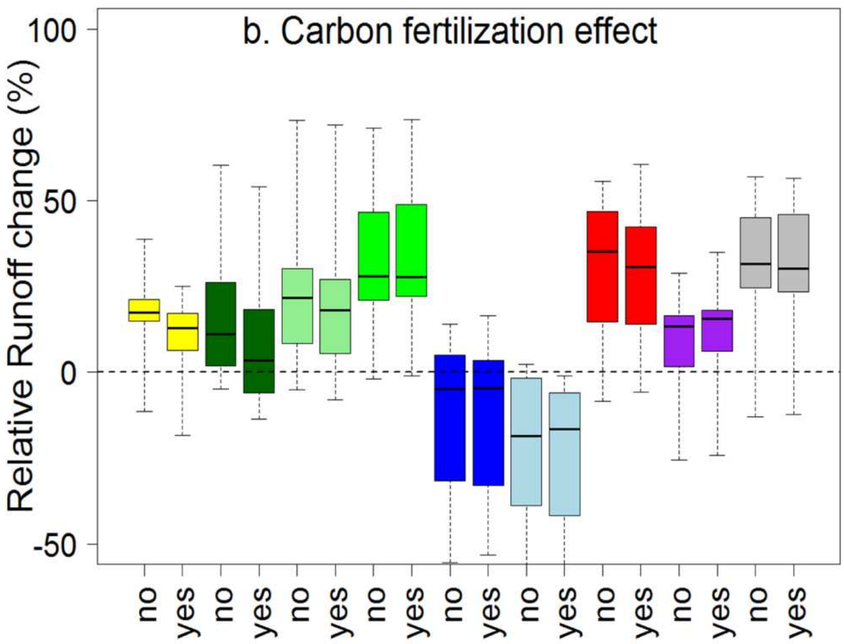
17. The text labels in some figures are difficult to read, particular in the Figs. 1 and 8 when compared to 3 or 4. Also the labels in the map (top Fig. 1), particularly the dark blue color impedes easy reading the name of the rivers. Although not a problem for a digital version of the paper, consider standardizing the size of the labels in the figures.

Referee #2 is right and we therefore redesigned Figs 1 and 8 to be easier to read (see attached)





a. Water Withdrawal
Relative Runoff change (%)
100
50
0
-50
Bani
Benue
Low Niger
Niger
Senegal
Gambia
Volta
Sassandra
All
no
yes
no
yes
no
yes
no
yes
no
yes
no
yes
no
yes
no
yes
no
yes



b. Carbon fertilization effect
Relative Runoff change (%)
100
50
0
-50
no
yes
no
yes
no
yes
no
yes
no
yes
no
yes
no
yes
no
yes
no
yes

Referee #3

- Overall Evaluation

This paper presents a thoughtful synthesis of a large number of studies that examine potential impacts to major rivers in West Africa. The paper points out that most of the research carried out to-date focuses on the effects due to climate change (via precipitation, temperature, and potential evapotranspiration), while a few also examine the effects of changes in water withdrawals, land-use, and atmospheric CO_2 concentration. The paper pulls together the results from many studies and provides insight to the state of our understanding of potential changes to West African rivers. Below, I offer a few suggestions to provide additional context for the synthesis and improve the communication of the results and implications. Overall, I think the paper makes a valuable contribution to our understanding of West African hydrology.

Thank you.

- Specific Suggestions

To help orient the readers who may be less familiar with West African rivers, I recommend that the authors include a table with some basic information about the river basins. Specifically, I recommend that they include: river name, mean annual flow, watershed area, river length, mean annual precipitation over the basin, and average aridity index (PET/P). Such information will be especially helpful when interpreting the results that are presented river-by-river. Additionally, I think the discussion of the sensitivity of river discharge to changes in precipitation would be improved if put into the context of some theory. Specifically, Budyko-type curves provide a first-order estimate of river runoff as a function of mean annual precipitation and PET. Using such a curve could provide a theoretical prediction of what the sensitivity of discharge to precipitation might be, and the results from the range of studies (as expressed in figure 6) could then be discussed in reference to that theory. Specifically, the relatively simple curve of Schreiber, 1904, provides a relationship between mean annual runoff (R), precipitation (P), and potential evapotranspiration (PET):$R = P * \exp(-PET/P)$
Using this equation, the sensitivity of runoff to changes in precipitation can then be expressed as
$(dR/R)*(P/dP) = 1 + PET/P$
The left-hand-side represents the ratio of the percent change in rainfall relative to the percent change in precipitation – the slope of the lines given in figure 6. Those slopes could then be compared to the term on the right-hand-side and differences or similarities discussed. And, of course, one could use the Budyko curve (1974) or other formulation instead of the equation from Schreiber. This would provide a nice theoretical framework for the interpretation of the variability among the river basins.

We added a table describing the parameters suggested by referee #3. However, we do not provide rainfall and PET as we do not have access to PET values over all the basins and as the map provides already a first assessment of the average rainfall for each basin (we added the watershed borders to the map).

River	Mean annual flow	Catchment area	Length of upstream mainstem (and total length)
Niger (Malanville)	1053 m^3/s	1000000 km^2	2367 km (3478 km)
Senegal (Dagana)	687 m^3/s	268000 km^2	1550 km (1757 km)
Black Volta (Bamboi)	263 m^3/s	134200 km^2	843 km (1355 km)
White Volta (Pwalagu)	125 m^3/s	63350 km^2	555 km (1334 km)
Volta (outlet)	1106 m^3/s	394100 km^2	1245 km
Gambia (Gouloumbou)	149 m^3/s	42000 km^2	451 km (799 km)
Sassandra (Soubre)	331 m^3/s	62000 km^2	-
Bani (Mopti)	1101 m^3/s	281600 km^2	1004 km (3457 km)
Benue (Yola)	22 m^3/s	107000 km^2	431 km (1541 km)

Table 1: characteristics of the selected rivers. All values come from the Global Runoff Data Centre (GRDC).

We moreover thank referee #3 for his idea of adding Budyko-type curves. This would be indeed a very interesting analysis but we are limited here by the information available in the papers that we reviewed: very few of them give PET and rainfall changes and almost none of them provide the raw values (not changes) of these variables, so unfortunately it is not applicable to this database.

- Language and Technical Correctness

Overall, the paper is well written. There are a few places where the use of language could be improved (see some specific examples below). I also offer some comments on how the figures might be enhanced as well.

Figure 5: As I understand it, the goal of this figure is to present the relationship between changes in river discharge to changes in temperature and rainfall. Visually, however, the primary message is a relationship between changes in temperature and changes in rainfall, and only secondarily about discharge. I suggest eliminating this figure and replacing it with one that is similar to figure 6, but which plots change in discharge versus change in temperature. Doing so would reveal the clear dependence of discharge on precipitation and the lack of dependence of discharge on temperature in a more effective way.

We followed Referee #3 advice and plot the following figure showing temperature change vs. discharge change.
However, we decided to keep the previous one as its main aim is to compare the effect of temperature and rainfall on runoff, to select the parameter with the largest influence and to study

it in the next figure more precisely (fig 6). If we put the suggested figure (below), it is not obvious to demonstrate if a negative runoff change is negative because of the temperature change or because of the rainfall, as rainfall is not shown.

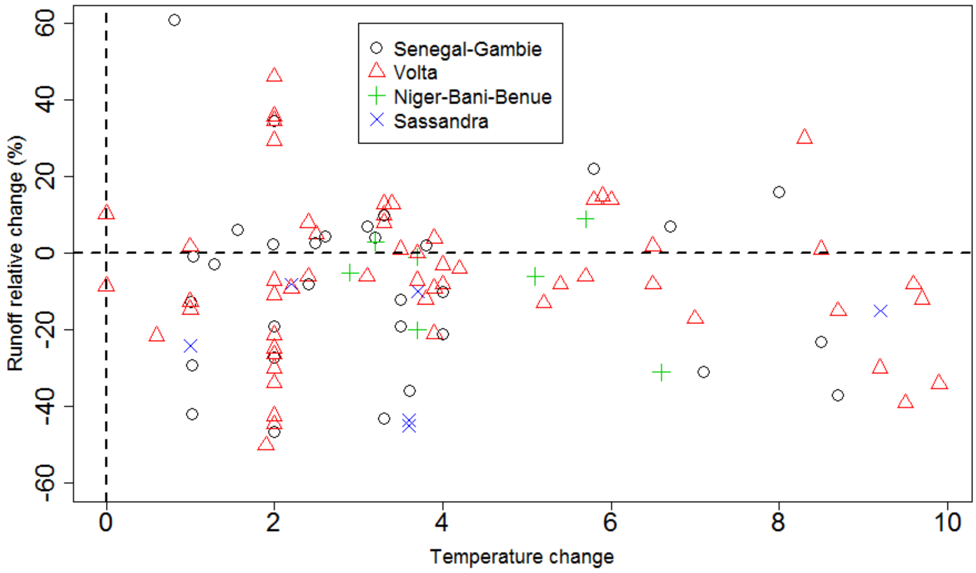


Figure 6: In addition to the general conclusion that runoff is sensitive to rainfall, the authors might wish to quantify (perhaps right on the figure or in a separate table) the sensitivities and their variability among rivers. That would enable the reader to compare among the basins in a quantitative way, and compare those values to the river characteristics (see comment about adding a table) and theory (see comment about Budyko-type curve)

Referee #3 is right and this is what we tried to do by adding the linear model for each river, and for the whole distribution. As explained before, it is unfortunately not possible to use Budyko-type curves here but we added a table with the regression equation of each line in order to quantify more precisely the differences among rivers.

River	Equation	Pearson correlation coefficient
Senegal-Gambie	Runoff change=1.3*rainfall change + 8.0	0.59
Volta	Runoff change=1.6*rainfall change - 10.6	0.77
Niger-Bani-Banue	Runoff change=2.0*rainfall change - 12.6	0.91
Sassandra	Runoff change=2.0*rainfall change + 7.7	0.68
All	Runoff change=1.6*rainfall change - 6.5	0.73

Table 2: Regression equation between rainfall change and runoff change, for each of the river.

Figure 7 – I interpret the warm colors to mean a reduction in monthly flow and the greens to indicate an increase; I recommend that it be articulated explicitly in the caption which colors indicate a increase and which a decrease.

Referee #3 is right, we modified the figure.

In the abstract and conclusions, I recommend that the phrase “much more” be eliminated – the contrast is between positive and negative, not positive and much more positive.

In section 2.1, line 15 I believe this statement is intended to be about intra-annual variability (not interannual variability). If so, I recommend eliminating the phrase “variations in” and replacing inter annual with intra-annual.

In section 2.3, I recommend separating the first paragraph into two (with the separation coming just before the phrase, “To create the database...”).

Corrections made as recommended by referee #3

I also recommend that the first part of that section be expanded a bit to give the reader a clearer sense of the overarching approach – that the studies related to climate are integrating into a database and assessed quantitatively, whereas the works addressing water withdrawals and carbon are treated more as case studies.

We modified this section in order to be more precise:

“Note that to be consistent with the other studies dealing only with climate change, we did not put the results including water use and land use changes in the database and thus we did not use them in section 3.1 to 3.3. More precisely, for McCartney et al. (2012) and Murray et al. (2012), we only kept the ‘climate only’ scenario. The other scenarios were used in section 3.4, as case studies.”

Throughout – rather than the phrase “contrasted climatic and hydrological conditions”,
I recommend “varying climatic and...”

Corrections made as recommended by referee #3

Referee #4

This work is very interesting on climate change models and prediction of river flows. A very positive point concerns the study area which covers the entire West Africa. The predicted results are much contrasted, with high uncertainty. The major finding is that changes in rainfall would be the main factor affecting rivers flows. But not any clear trend is depicted. This finally raises the issue of the validity of climate models. How the accuracy of these models can be improved in future studies is also quite well addressed in the manuscript. However, in its current state, the work is reserved for quite a small audience, familiar with climate models. I fear that the interest of such an important work escapes most JHESS readers.

I recommend to the authors, insofar as the paper is a review of results from various models, to include in the manuscript a section giving the principles of these models and scenarios, whether simple or advanced ones.

We added some details about emissions scenarios and climate models:

"***Most studies used climate variables directly from General Circulation Models (GCMs) or Regional Circulation Models (RCMs) that simulate climate variables using physical equations representing the circulation of the atmosphere and/or ocean. GCMs/RCMs can differ in terms of the conceptualization and parameterization of processes, as well as in their spatial resolution, which is typically circa 2.5° for GCMs and 0.5° for RCMs. To simulate the response of the global climate system to increasing greenhouse gas (GHG) concentrations these models were forced by future GHG emission scenarios. Many different types of scenarios are available and are clustered in three main groups, that were created in chronological order and used for the different IPCC reports: the early IS92 (Leggett et al., 1992) including for example scenario IS92a or IS92c, the SRES (Special Report on Emission Scenario, see Nakicenovic and Swart (2000) for a description) with e.g. A1B, A2 or B1 and the RCPs (Representative Concentration Pathways, Moss et al. (2010)) used in the fifth IPCC report (RCP 4.5, RCP 2.6, RCP 8.5). Each group is constituted by contrasted scenarios representing low level of GHG emissions (e.g. for the SRES, scenario B1 that leads in 2100 to an average warming of +1.9C) or high level (A2, that leads to +3.1C, see Meehl et al. (2007)).”***

A presentation of the six basins selected for this work (Niger, Volta, Senegal, Gambia, Sassandra) would be also helpful. The paper is well organized and written. Captions of some figures should be expanded, as they are too small and almost unreadable.

We added a table describing the parameters suggested by referee #4 and we added the basins borders to the map. We also expanded the labels, see below:

River	Mean annual flow	Catchment area	Length of upstream mainstem (and total length)
Niger (Malanville)	1053 m^3/s	1000000 km^2	2367 km (3478 km)
Senegal (Dagana)	687 m^3/s	268000 km^2	1550 km (1757 km)
Black Volta (Bamboi)	263 m^3/s	134200 km^2	843 km (1355 km)
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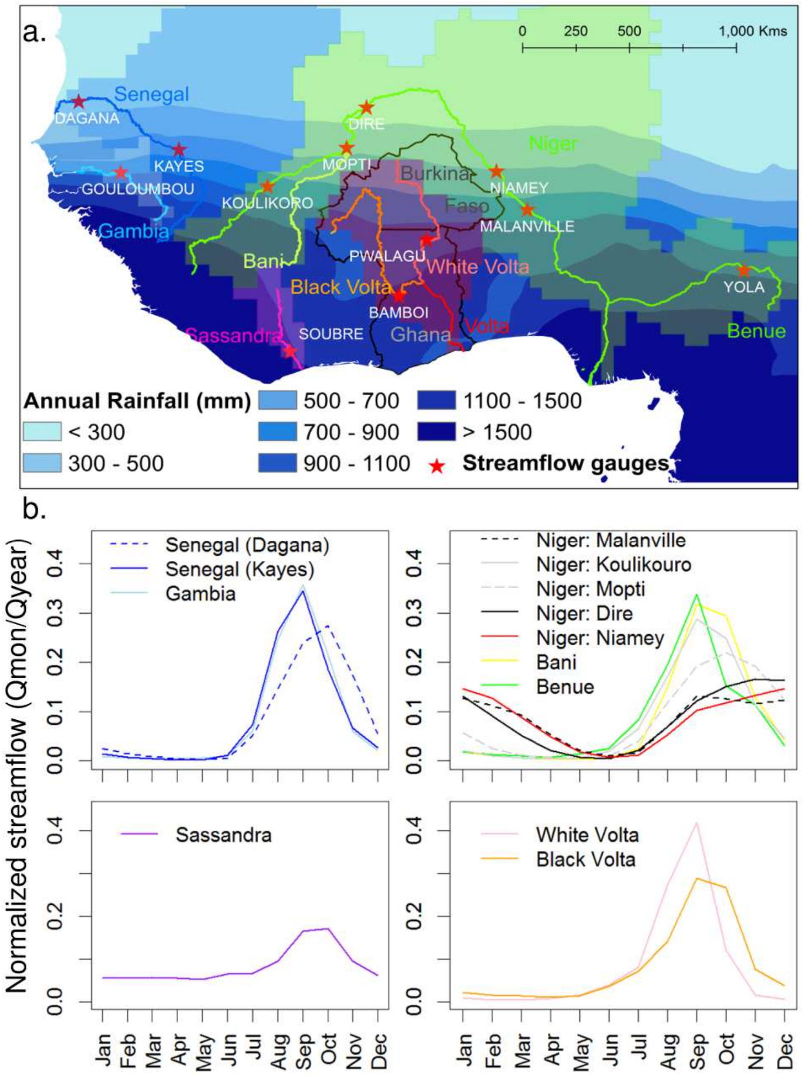
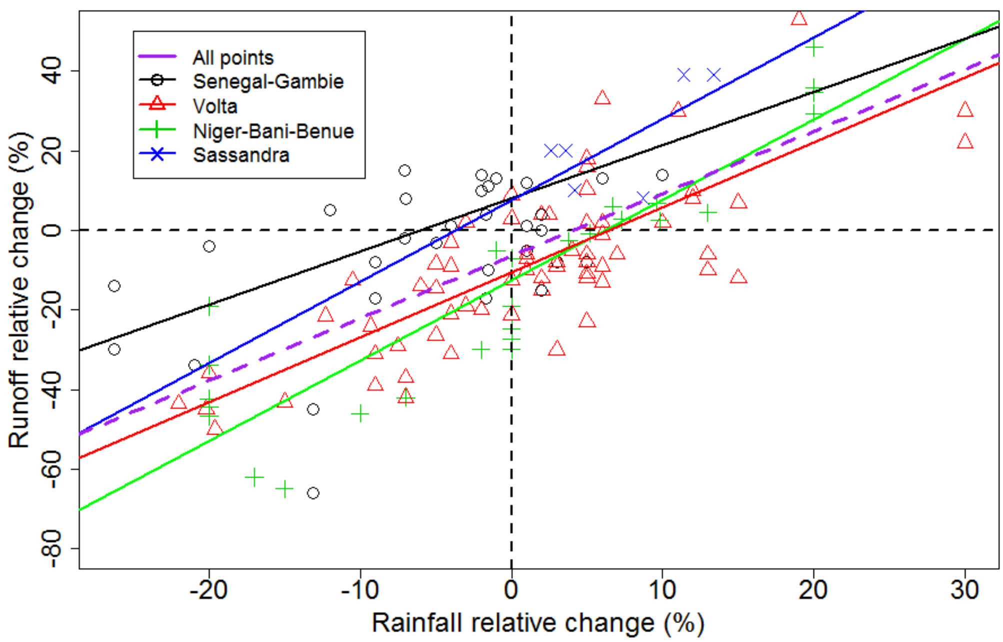
Volta (outlet)	1106 m^3/s	394100 km^2	1245 km
Gambia (Gouloumbou)	149 m^3/s	42000 km^2	451 km (799 km)
Sassandra (Soubre)	331 m^3/s	62000 km2	-
Bani (Mopti)	1101 m^3/s	281600 km^2	1004 km (3457 km)
Benue (Yola)	22 m^3/s	107000 km^2	431 km (1541 km)

Table 3: characteristics of the selected rivers. All values come from the Global Runoff Data Centre (GRDC).


a.
0 250 500 1,000 Kms
Senegal
DAGANA
DIRE
KAYES
MOPTI
Niger
GOULOUMBOU
Burkina
NIAMEY
KOULIKORO
Faso
MALANVILLE
Gambia
PWALAGU
Bani
White Volta
Black Volta
YOLA
BAMBOI
Sassandra
SOUBRE
Ghana
Volta
Benue
Annual Rainfall (mm)
< 300
300 - 500
500 - 700
700 - 900
900 - 1100
1100 - 1500
> 1500
Streamflow gauges
b.
Normalized streamflow (Qmon/Qyear)
Senegal (Dagana)
Senegal (Kayes)
Gambia
Niger: Malanville
Niger: Koulikouro
Niger: Mopti
Niger: Dire
Niger: Niamey
Bani
Benue
Sassandra
White Volta
Black Volta
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec



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