

Climate change impacts on runoff in West Africa: a review

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Abstract: This review summarizes the impacts of climate change on runoff in West Africa, assesses the uncertainty in the projections and describes future research needs for the region. To do so, we constitute a meta-database made of 19 studies and 301 future runoff change values. The future tendency in streamflow developments is overall very uncertain (median of the 301 points is 0% and mean +5.2%), except for (i) the Gambia River which exhibits a significant negative change (median=-4.5%) and (ii) the Sassandra and the Niger Rivers where the change is positive (+14.4% and +6.1%). A correlation analysis revealed that runoff changes are tightly linked to changes in rainfall ($R=0.49$), and to a smaller extent also to changes in potential evapotranspiration. Other parameters than climate such as the carbon effect on plant water efficiency, land use dynamics or water withdrawals could also significantly impact on runoff, but they generally do not offset the effects of climate change. In view of the potential changes, the large uncertainty therein, and the high vulnerability of the region to such changes, there is an urgent need for integrated studies that quantify the potential effects of these processes on water resources in West Africa and for more accuracy in climate models rainfall projections. We especially underline the lack of information concerning projections of future floods and droughts, and of inter-annual fluctuations in streamflow.

Keywords: West Africa, climate change, river discharge, hydrology

1. Introduction

2

3 Surface water is fundamental for many sectors in West Africa (WA) including agriculture, power
4 generation and fisheries. Even if most of the agriculture in the area is rainfed, some regions strongly
5 depend on surface water. For example, the *Office du Niger* produces 40 to 50 % of rice production of
6 Mali (Bélières et al., 2011) thanks to the Markala dam on the Niger River. Surface water collected
7 through big dams on large rivers is also a major source of power generation in WA. The Niger River, for
8 example, has currently a 2004 MW maximum power generation (Skinner et al., 2009) and this value
9 could increase in the future as the power demand is dramatically increasing (+17%/year). Finally,
10 fisheries strongly rely on river discharge. The drought conditions occurring in WA in the 70s and 80s
11 caused a drop of -50% in fisheries production of the Niger Delta, resulting in a loss of about 20 million
12 US\$ per year (Neiland and Béné, 2008).

13 River discharge is affected by several drivers such as land use changes, water withdrawals and
14 climate variations. As underlined by the above example, variability in climate, and especially in rainfall,
15 plays a significant role in flow variation. In view of global warming, which will affect key climate variables
16 such as rainfall and temperature, changes in hydrological regimes could become even more important in
17 the future (Wuebbles and Ciuro, 2013). In combination with the increasing demographic pressure and
18 low adaptive capacity, these changes could therefore have significant impacts on people and sectors
19 that depend on the availability of water in WA. As stated by UNECA and ACPC (2011), there is thus a
20 need to study the impacts of climate change on runoff regimes in Africa and to assess the uncertainty of
21 such projections. This is particularly true for West Africa where “little work has been done on the future
22 impact of climate change on water resources” (ENDA-TM, 2007).

1 To date, relatively few studies have assessed the impacts of climate change on hydrological regimes
2 in WA and a clear picture of possible changes is lacking. In order to fill this gap, we perform a review of
3 the existing literature to summarize the impacts of climate change on runoff in WA, to assess the
4 uncertainty of the projections and to describe future research needs for the region. More specifically,
5 we build a meta-database with the results of the available studies (section 2.3), and we use it in section
6 3 to (i) quantify the overall impact of climate change on mean annual discharge in WA, (ii) focus
7 specifically on each river of the area, (iii) study the relative role of climate variables in discharge
8 evolution, (iv) detail how extremes and interannual variability could change in the future, and (v) assess
9 the impacts of climate vs. the impacts of other drivers such as land use, water withdrawal and increasing
10 carbon concentration.

11

12 2. Area and Methodology

13

14 2.1 Area

15 We focus in this review on some of the main West African rivers (Figure 1a and Table 1): Niger,
16 Volta, Senegal, Gambia and Sassandra Rivers. We did not find in the existing literature studies about
17 other West African rivers, or they were not directly usable. WA is a region with very different climatic
18 conditions. Its northern part is dry (between 300 and 500 mm/year for the so-called *Sahelian* area, see
19 FAO (2004)) while the south is much wetter, with some areas receiving more than 2000 mm/year. In the
20 part where annual precipitation is below 1100 mm/year, encompassing the *Sahelian*, *Sudano-Sahelian*
21 (500-900 mm/year) and *Sudanian* areas (900-1100 mm/year), rainfall occurs during a single rainy season
22 whose core months are July, August and September which is caused by the shift of the Intertropical

1 Convergence Zone (ITCZ) to the north (Sultan, 2002). In the southernmost area, called *Guinean* (>1100
2 mm/year) there are two rainy periods, namely the short one ranging from September to November and
3 the long one, from March to July, that are occurring at each passage of the ITCZ. The seasonal pattern of
4 rainfall leads to strong intra-annual streamflow variations. Figure 1b shows the average hydrographs for
5 the selected rivers, based on the rescaled flow ($Q_{\text{month}}/Q_{\text{year}}$). They underline the differences among
6 rivers (e.g. Niger vs. Senegal) but also within a river basin. The latter is because the drainage basins of
7 some rivers in WA can be very large, especially for the Niger (circa $2.1 \cdot 10^6 \text{ km}^2$), and as a consequence
8 includes strongly contrasted climatic and agro-ecological regions. The Upper Niger River hydrograph
9 (Mopti, Koulikouro, Bani River), for example, depicts a much sharper high flow peak than its
10 downstream counterpart (Niamey, Malanville, Dire) because of the size of the basin, and because of the
11 inner delta, where peak discharge is strongly attenuated by flooding and evaporation. This is also
12 expressed by the time of occurrence of high flows, which is in September-October for the upstream
13 Niger reaches, and December-January for the more downstream ones.

14 *FIG 1 about here*

15

16 **2.2 Factors influencing runoff**

17 In order to assess future runoff changes, four key processes have to be taken into account (Sterling et al,
18 2013):

- 19 - Climate variability and change. Several studies have shown that discharge evolutions over the
20 past decades in WA have been strongly affected by rainfall variations. After the wet 50s and 60s,
21 a strong rainfall deficit happened since 1970 in the Sahelian and Sudano-Sahelian areas (e.g.
22 Paturol et al. (2003)) with some dramatic droughts like the 1973/74 and 1983/84 ones. Recent
23 studies such as Lebel and Ali (2009), however, suggest a recovery of the rain in eastern parts of

1 WA, whereas drought conditions endure in western regions. These rainfall variations have led to
2 strong fluctuations in river discharge with a general negative trend from 1960 to 2010 (Descroix
3 et al., 2013), especially in Sudanian areas. In Guinean areas the decrease has been more
4 moderate. Mahe et al. (2013) underlined the non-linear effect of this rainfall drop over much of
5 WA, with a -20% decrease in rainfall resulting in a decrease of -60% in runoff.

6 Climate models project important climate changes for the 21st century, in WA as well as
7 in the rest of the world, with potential impacts on the hydrological cycle. Projections all agree on
8 a warming in WA even though its magnitude ranges from +2°C to +6°C in 2100 across climate
9 models (Christensen et al., 2007). These models, however, do not agree on the sign of the future
10 evolution of precipitation. Almost half of them predict an increase in rainfall and the other half a
11 decrease (Vigaud et al. (2011); Berg et al. (2013)), but changes could still be important (roughly
12 ranging from -20% to +20% in annual rainfall, see Sultan et al. (2013)). More robust results have
13 been reported regarding monthly anomalies of the rainy season in WA, with a delayed onset
14 and offset and shortening of the rainy season (Biasutti and Sobel, 2009). Similar results are
15 described in Patricola and Cook (2010).

16 - Changes in Land use. In recent decades WA has seen major changes in land use, with strong
17 impacts on runoff (Wittig et al., 2007). For some rivers located in the Sahelian zone, discharge
18 has increased, even with the drop in rainfall, because of considerable land use changes driven by
19 demographic pressures. This is known as the *Sahelian paradox* (see e.g. Mahe et al. (2005) for
20 the Nakambe River). The extension of cropped areas combined with the shortening of fallow
21 periods (Mortimore et al., 2005) has led to soil degradation and superficial crusting, hereby
22 limiting infiltration and increasing runoff (Leblanc et al. (2008); Descroix et al. (2012)).

23 - Changes in water consumption/withdrawals. This factor may have an important impact on
24 runoff in a region where the population is growing fast. For example, in WA water withdrawals

1 have increased by 31% between 1983/1987 and 1998/2002 (Aquastat¹). This value could
2 increase much more in the future as food demand could quintuple by 2050 in the region
3 (Collomb, 1999).

- 4 - Carbon effect on plant water use. Rising CO₂ concentration could alter vegetation water use
5 (and thus the water cycle) through two opposite effects (Tubiello et al. (2007); Leakey (2009);
6 Alkama et al. (2010)): (i) lower stomatal conductance which leads to a reduction in potential
7 evapotranspiration (PET) and (ii) enhanced photosynthesis which leads to an increase in Leaf
8 Area Index and an increase in PET. Even though the effects of increased atmospheric CO₂ levels
9 on discharge remains highly uncertain, some global studies like Gerten et al. (2008) and Shi et al.
10 (2011) have demonstrated that this carbon effect may have had a non-negligible impact on
11 runoff.

14 **2.3 Database**

15 We collected all studies that have evaluated the effects of these major drivers on future runoff
16 regimes in WA. Most studies have focused on the effects of climate variables changes. We constructed a
17 database storing results of this latter effect. For this ensemble of projections, representing a wide
18 variety of models, scenarios and methodologies, we quantify changes in runoff characteristics and the
19 uncertainty therein. On the other hand, only few studies have addressed the other drivers of runoff
20 change: therefore, results from these papers are not included in the database and are summarized
21 herein in a more qualitative manner.

¹ http://www.fao.org/nr/water/aquastat/water_use/index.stm

1 To create the database, we followed a methodology close to Roudier et al. (2011): we selected 16
2 peer-reviewed papers or conference proceedings, 1 PhD thesis and 2 official reports published since
3 2000 that focus on runoff/discharge changes in WA (ECOWAS countries + Cameroon) in view of climate
4 change, only (Table 1). Milly et al. (2005) and Arnell (2004) were excluded from the database because it
5 was not possible to access the detailed results at the river or regional scale or because they do not focus
6 on the selected variables. These studies were however used in the discussion. The final database
7 includes 301 runoff change values defined by different rivers, climate models, emission scenarios, time
8 horizons and hydrological models.

9 Most studies used climate variables directly from General Circulation Models (GCMs) or Regional
10 Circulation Models (RCMs) that simulate climate variables using physical equations representing the
11 circulation of the atmosphere and/or ocean. GCMs/RCMs can differ in terms of the conceptualization
12 and parameterization of processes, as well as in their spatial resolution, which is typically circa 2.5° for
13 GCMs and 0.5° for RCMs. To simulate the response of the global climate system to increasing
14 greenhouse gas (GHG) concentrations these models were forced by future GHG emission scenarios.
15 Many different types of scenarios are available and are clustered in three main groups, that were
16 created in chronological order and used for the different IPCC reports: the early IS92 (Leggett et al.,
17 1992) including for example scenario IS92a or IS92c, the SRES (Special Report on Emission Scenario,
18 Nakicenovic and Swart (2000)) with e.g. A1B, A2 or B1 and the RCPs (Representative Concentration
19 Pathways, Moss et al. (2010)) used in the fifth IPCC report (RCP 4.5, RCP 2.6, RCP 8.5). Each group is
20 constituted by contrasted scenarios representing low level of GHG emissions (e.g. for the SRES, scenario
21 B1 that leads in 2100 to an average warming of +1.9°C) or high level (A2, that leads to +3.1°C, see Meehl
22 et al. (2007)). The simulated climate variables were then used as inputs in an offline hydrological model
23 (e.g. Falloon and Betts (2006); Kamga (2001)). Some studies however did not use directly these climate
24 models but made some assumptions about the future climate to generate potential time series (e.g.

1 +2°C and -5% for rainfall, Okpara and Perumal (2009)). Since such scenarios are within the range of
2 potential evolutions simulated by the GCMs, we decided to include them in the database.

3 Furthermore, some works like McCartney et al. (2012) and Karambiri et al. (2011) included a
4 downscaling step between the climate and hydrological model, through either Regional Climate Models
5 (RCMs), a delta change approach (van Vliet et al., 2013) or a weather generator (Kankam-Yeboah et al.,
6 2013). We chose in this review to put together all these methodologies, even if some of them are quite
7 simple, rather than focusing on the most advanced ones, in order to give the best estimation of the
8 uncertainty of the results.

9 Concerning the other drivers of runoff change, McCartney et al. (2012) and Murray et al. (2012)
10 used scenarios of water use change, Murray et al. (2012) dealt with the effects of increased atmospheric
11 carbon concentration on runoff, and no study accounted for land use dynamics. Note that to be
12 consistent with the other studies dealing only with climate change, we did not put the results including
13 water use and land use changes in the database and thus we did not use them in section 3.1 to 3.3.
14 More precisely, for McCartney et al. (2012) and Murray et al. (2012), we only kept the 'climate only'
15 scenario. The other scenarios were used in section 3.4, as case studies.

16

17 3. Results

18 3.1 Impact of climate change on yearly mean discharge

19

20 3.1.1 Over the whole region

21 Even though the region is characterized by varying climatic and hydrological conditions we first
22 evaluated if a general climate signal could be detected in future streamflows across the whole study

1 area. To do so, all the points contained in the database, representing different rivers, time periods and
2 methods, were pooled and a distribution was constructed of the projected relative changes in mean
3 annual river flows (i.e. $((Q_{\text{future}} - Q_{\text{present}})/Q_{\text{present}})*100$). The latter is presented in Figure 2 which depicts a
4 high peak close to 0%, expressed by the median=0%, the mean=+5.2%, and a very high range of
5 potential future changes, from -100% to +260%. As discussed more in detail further herein, this is due to
6 the use of different scenarios and models, but it also largely relates to the contrasted climatic zones of
7 WA and the different projected climate changes therein. As almost 40% of the database is constituted
8 by data from the World Bank study (Strzepek and McCluskey, 2006), we next randomly deleted 50% of
9 this study's results in order to assess the robustness of our findings. We repeated this step 30 times and
10 computed the resulting median. We did also the same experiment deleting 20% of the whole database..
11 The results reveal that the median value found before is quite robust: it is indeed always (out of 60 tries)
12 between -2% and 2%.

13 *FIG 2 about here*

14 The studies that were not contained in the database for reasons previously discussed do not agree
15 either on the sign of runoff change in WA. Milly et al. (2005) found a slight negative trend and Paturel et
16 al. (2007) concluded on a much more negative one, largely due to the use of a quite pessimistic scenario
17 (PET +5%; Rainfall -10%, doubling CO₂). On the other hand, Arnell (2004) found that by 2055 in WA
18 much less people would be affected by water stress, whereas Faramarzi et al. (2013) projected no
19 change or a small increase in surface water and groundwater availability in most of West African
20 countries.

21 Figure 2 focuses on all points in the database, hereby mixing projections across different time
22 horizons. To evaluate if the predicted impacts may be more pronounced by the end of the 21st century
23 because of rising greenhouse gases concentrations we split the database in two parts based on the time

1 horizon studied: early 21st century (2020-2060) and late 21st (2061-2100). Figure 3 shows that the
2 selected future time period does not strongly influence the overall sign of future runoff evolution: the
3 median for the early 21st century is indeed 0% and +2% for the late 21st century, but the difference is not
4 significant. It is however important to note that both panels (early and late) do not include the same
5 rivers, models or scenarios. The increase in interquartile range as time proceeds nevertheless suggests
6 that signals of change become more pronounced with increasing greenhouse gas levels. This is also
7 confirmed when evaluating the projections of individual studies that consider different time horizons. In
8 68% of the cases, the impact of climate is more evident in the late 21st, especially when the emission
9 scenario taken into account has very contrasted radiative forcing between late and mid-century.
10 Ruelland et al. (2012), for example, project a runoff evolution of -5 % by 2025 and -65% by 2085, using
11 the SRES A2 scenario.

12 *FIG 3 about here*

13

14

15 *3.1.2 Impact by river*

16 To evaluate projections in different regions of WA we clustered river basins or areas under the
17 following labels: Niger is: Niger, Bani and Benue; Volta is: White Volta (or Nakambe), Black Volta,
18 Burkina Faso (country using results of Strzepek and McCluskey (2006)) and Ghana (country). For the
19 Senegal and Volta Rivers, Figure 4a shows that the median change is not statistically different from 0,
20 which means that the impact of climate change is small or not clear, even if it could potentially be very
21 strong in some cases. For the Gambia River a small but significant negative trend is projected (median=-
22 4.5%), whereas a positive significant evolution in river flows is projected for the Sassandra (+14.4%) and

1 the Niger River (+6.1%). It is however important to note that the positive trend for the Niger River is
2 mainly due to Aich et al. (2014), which represent 40% of the selected runoff changes.

3 We next focus on the heterogeneity of the results for the Niger River which covers very different
4 climatic zones (Figure 1a) that may show dissimilar responses to climatic variations and future climate
5 projections (e.g. lower temperature increase near the coasts). Thus, in order to detail more carefully the
6 changes in the Niger River basin, we evaluate results separately for the *lower Niger* (i.e. the basin
7 downstream Niamey and the Benue River), the *Upper Niger* (Bani included) and the *Niger River*
8 representing the cases where only *Niger* was quoted in the papers. Figure 4b confirms that there is a
9 wide range in the possible runoff evolutions even for a restricted part of the Niger River basin. Indeed,
10 for the Bani river located in the upper part of the Niger basin, Murray et al. (2012) found a positive
11 pattern in future streamflow that contradicts with the strong negative trend obtained by Ruelland et al.
12 (2012). Moreover, there is no particular trend for the lower Niger, mainly due to papers on the Benue
13 Rivers, but a positive one is found for the Niger River, globally as well as in its upper part. However, it is
14 necessary to underline that, in a paper not included in the database, Paturol et al. (2007) projected the
15 strongest negative river flow evolutions for the inner delta of Niger and the *Fouta Djallon* area. All these
16 results show that future studies should focus more on the heterogeneity of the runoff change over the
17 Niger basin.

18 *FIG 4 about here*

19

20 **3.2 Relative role of Rainfall and temperature in discharge evolution**

21 In this section we evaluate which parameters are the major drivers of the changes described in
22 the previous section. We focus here on temperature, rainfall and PET, when the anomalies for these

1 variables are available in the selected studies. Figure 5 shows the rainfall and temperature future
2 changes associated with the runoff relative change. Qualitatively, this plot depicts a stronger effect of
3 rainfall on runoff changes compared to temperature, with negative runoff values (orange and red)
4 corresponding mainly to negative rainfall anomalies. This is confirmed by the Pearson correlation
5 coefficients between changes in runoff and in the three variables. While rainfall is the dominating factor
6 ($R=0.49$, significant at 1%) for river flow evolution, also PET plays an important, although opposite, role
7 ($R=-0.35$, significant at 5%). Although temperature indirectly affects streamflow through PET, no
8 statistically significant relation ($R=-0.04$, not significant) was found between the projected temperature
9 and streamflow changes. These results are in accordance with earlier findings in the literature which
10 underline the major role played by rainfall on future runoff changes (Kundzewicz et al., 2007) and its
11 sensitivity to PET (UNECA and ACPC, 2011). Applying a similar correlation analysis, Murray et al. (2012)
12 found similar results for rainfall ($R=0.53$) for the Niger. The dominant role of rainfall for streamflow
13 generation and the fact that projections of rainfall, especially with regard to the monsoon, remain to
14 date highly uncertain (see section 2.2) partly explain the contrasting results found among studies,
15 depending on the chosen rainfall scenario.

16 To analyze the elasticity of runoff to precipitation (Guimberteau et al., 2013) in different parts of
17 the area, we plot in Figure 6 the future changes in runoff vs. those in rainfall for the four main rivers and
18 for the whole area. The variation in steepness of the fitted linear regression lines shows that rivers in
19 WA react differently to the same drop or increase in rainfall (Table 3). The highest sensitivity to rainfall
20 changes is found in the Niger and Sassandra, although for the latter basin data points are only available
21 for positive changes in precipitation. Aich et al. (2014), doing the same kind of analysis for the Niger but
22 with annual values found an even stronger sensitivity to rainfall: according to their study, a +25%
23 increase in rainfall would lead to +90% increase in runoff. The lowest sensitivity is found for
24 Senegal/Gambia, but the underlying values come from only one study. The fitted lines do not intersect

1 the y-axis at zero but at different points along the y-axis. If so, this would imply no change in river runoff
2 for no change in rainfall. Here, however, this shift is related to catchment-specific sensitivities of runoff
3 to changes in PET and T as well as to uncertainties in the hydrological model in translating climate inputs
4 to runoff. These effects that are not caused by rainfall changes seem strongest for the Niger and Volta
5 rivers (circa -12%, close to Aich et al. (2014), for the Niger River). Their overall impact is about -8% taking
6 all rivers and warming scenarios into account, and a 10% drop in rainfall would result in a reduction in
7 river flow of approximately 25%.

8 *FIG 5 and 6 about here*

9 **3.3 Impacts of climate change on intra-annual variability and extremes**

10

11 Most studies contained in the database focus solely on annual discharges. Some studies, however,
12 also detailed the impacts of future climate on monthly values and extreme river flows. We summarized
13 the results for each river and present a qualitative assessment in Figure 7 and Table 4. To date, only
14 McCartney et al. (2012) has focused in WA on the potential effect of climate change on the magnitude
15 of floods for a range of return periods. By the end of this century, the magnitude of frequent floods
16 (with return periods less than 10 years) is projected to decrease in the Volta River, whereas the trend for
17 higher return periods floods (i.e. more extreme) is not consistent from station to station. Moreover,
18 Jung et al. (2012) and Kunstmann and Jung (2005) found an increase in runoff in September when flows
19 in the Volta are typically the highest (Figure 1b). For the Senegal, Gambia and Sassandra Rivers, on the
20 other hand, high flows (September and October) are projected to decrease (Ardoin-Bardin et al., 2009).
21 On the Niger River, results depend on the area studied but some agreements seem to arise on (i) a later
22 occurrence of the peak flows (Murray et al. (2012), Falloon and Betts (2006)) and (ii) an increase of peak
23 flows (Kamga (2001), van Vliet et al. (2013), Falloon and Betts (2006)). However, this is only a global

1 pattern. As underlined by Aich et al. (2014), the results strongly depend on the climate model used and
2 also on the area. On the Bani River which is a tributary of the Niger, Ruelland et al. (2012) found indeed
3 a strong decrease in maximum monthly runoff. These findings show that there is currently insufficient
4 information to make strong statements about possible evolutions in West African hydrographs, although
5 any such changes would be a major concern for flood protection, dam design or socio-economic
6 activities depending on water availability (Roudier and Mahé, 2010).

7 *FIG 7 and Table 2 about here*

8 **3.4 Impact of climate change vs. other factors**

9 As underlined in section 2, other drivers also affect runoff generation. These include the effect
10 of increased atmospheric carbon concentrations on plant water use efficiency (WUE) and leaf area
11 index, intensive water use and anthropogenic land use changes. In this section we evaluate to what
12 extent these other drivers control discharge, and whether their impact is negligible, or not, compared to
13 climate. Several works have looked at the marginal effects of these drivers on river flow in other regions
14 of the world, but only very few studies have addressed these issues in WA, resulting in only few data
15 points contained in the database (two studies accounted for water consumption, one for the carbon
16 effect, and none for land use dynamics).

17

18 *3.4.1 Carbon effect and water consumption*

19 McCartney et al. (2012) designed four different scenarios of water consumption whereas
20 Murray et al. (2012) accounted for the effects of water withdrawals and of atmospheric carbon increase.
21 Both studies underlined the potential of these drivers in altering streamflows but the changes they
22 induce are generally less important than the effects of climate change. McCartney et al. (2012) found an

1 average impact of climate change on runoff of -34% without water use changes and -43% with the *full*
2 *development scenario*. Similarly, Figure 8a, which summarizes the results of Murray et al. (2012), shows
3 that the effects of water withdrawals on future runoff can be considerable but do not reverse the
4 climate signal. Moreover, the effect of carbon on runoff depicted in Figure 8b seems to be smaller than
5 that of water withdrawal changes. In WA as a whole, the median change under the scenario with fixed
6 carbon concentration amounts to +31.6% while a +30.3% increase in runoff is projected when the
7 increase in carbon concentration is accounted for. However, as underlined by Murray et al. (2012), the
8 effect of higher carbon concentration on runoff is very different across WA: it can indeed cause a
9 decrease (e.g. Benue River) or an increase (Sassandra) in river discharge. These results are coherent with
10 past trends at the global scale on the relative share of land use, water consumption/withdrawal, climate
11 and carbon effect on retrospective runoff changes (Sterling et al., 2013).

12 *FIG 8 about here*

13

14

15 *3.4.2 Land use changes*

16 Gerbaux et al. (2009) for the Sahelian area and Sterling et al. (2013) at the global scale have
17 demonstrated that anthropogenic land use dynamics have been more or equally important as climate
18 change in past runoff evolution. These studies illustrate the very important role of land use changes on
19 hydrology. Despite this potential strong impact, we found only three studies that we did not include in
20 the database dealing with this issue. Oguntunde et al. (2012) showed that for different hypothetical
21 levels of reforestation in the Niger basin the runoff increases up to +25%. Meigh et al. (2005), on the
22 other hand, found almost no change when including land use in their analysis in WA. Finally, Cornelissen
23 et al. (2013), using several contrasted scenarios of future land use changes in Benin found that such

1 modifications could have a substantial impact on discharge. However, it strongly depends on the
2 hydrological model used. Further studies using socio-economic based land use change scenarios are thus
3 needed in order to assess precisely the role of land use in future discharge changes in WA.

4

5

6 4 Conclusion

7 To summarize the current state of knowledge on potential future streamflow evolutions in view of
8 global warming in West Africa, we created from all relevant available studies a database of 301 points
9 containing quantitative information on the impact of climate change on runoff in the region. We found
10 that there is no clear general pattern of future runoff evolution in this area (the median of the
11 distribution is 0% and the mean +5.2%, considering different time horizons, different rivers, scenarios
12 and models) but that potential changes could be very large in some rivers. The future tendency is still
13 very uncertain when looking at river basins separately, except for the Gambia River which exhibits a
14 significant negative change (median=-4.5%). For the Sassandra and the Niger Rivers however, the
15 change is positive (+14.4% for Sassandra, +6.1% for Niger) but still with a large range of potential
16 changes. The high variability in projections is due to the large area of the river basins and to very
17 contrasted rainfall changes predicted by the climate models, roughly from -20% to +20% on average
18 over West Africa. Correlation analysis revealed that runoff changes are tightly linked to changes in
19 rainfall ($R=0.49$), whereas PET is also significantly correlated to runoff. Only few studies focused on
20 month by month runoff evolution; that is why it is hard to find robust results on changes in intra-annual
21 variability. However, the maximum monthly river flow of the Niger River could increase in the future and
22 the peak flow could be delayed.

1 We also studied other factors influencing runoff such as land use, water consumption and the
2 effect of higher carbon concentration. Based on two studies, our results showed that the carbon effect
3 as well as water withdrawals can potentially have significant impacts on runoff changes, but they
4 generally do not offset the effect of climate change. Although land use changes have played a major role
5 in past runoff evolution in West Africa, only two studies have dealt with this issue, with contrasting
6 results. One study stated that the difference between “climate only” and “with land use changes”
7 scenarios could be up to 25%, whereas the other found very minor changes.

8 This review shows the need for more studies on the assessment of future water resources in West
9 Africa. Despite the general agreement about the high vulnerability of this area to climate change, there
10 is a real lack of studies focusing on this region. Future studies should look more in detail to high and low
11 flow variations which are fundamental for agriculture, fisheries and dams. There is also an urgent need
12 to take into account the other factors influencing runoff, especially water and land use changes, in order
13 to get a more comprehensive assessment and to guide the elaboration of sound adaptation strategies.
14 This can be achieved through the use of integrated process-based models that simultaneously include
15 the driving processes that link climate, carbon, water and terrestrial vegetation dynamics (Guimberteau
16 et al. (2014); Gerten (2013)).

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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)

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

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Paper	Area/River	Target time period	Climate model	Scenario	Hydrological model	Land use/ water use change/CF
Ardoin-Bardin et al. (2009)	Senegal, Gambia, Sassandra	2020, 2050 and 2080	HadCM3	A2	GR2M	no /no/no
Karambiri et al. (2011)	Nakambe	2011/2050	ECHAM5-KNMI, ECHAM5-MPI, HadCM3-SMHI	A1B	GR2M	no /no/no
Jung et al. (2012)	Volta	2030/2039	ECHAM4-MM5	IS92a	WaSIM	no /no/no
Oguntunde and Abiodun (2013)	Niger river	2031/2050	RegCM3	A1B	SUBEX (+BATS1E)	no /no/no
Ruelland et al. (2012)	Bani river	2011/2099	HadCM3 and MPI-M	A2	GR2M	no /no/no
Kunstmann and Jung (2005)	Volta	2030/2039	ECHAM4-MM5	IS92a	OSU-LSM ("infiltration excess")	no /no/no
McCartney et al. (2012)	Volta	1983/2012, 2021/2050 2071/2100	ECHAM5-CCLM	A1B	SWAT then WEAP	no/yes/no
Kasei (2009)	Volta	2025 (REMO) & 2035 (MM5)	ECHAM4-MM5 + REMO	IS92a (MM5) & A1B+B1 (REMO)	WaSiM-Volta	no /no/no
Obuobie and Diekkrüger (2008)	white Volta	2030/2039	ECHAM4-MM5	IS92a	SWAT	no /no/no
Okpara and Perumal (2009)	Niger	None	None. Hypothetical scenarios	Rainfall/Temp. (+2C)	Thornwaite simple bucket wat. Bal. model	no /no/no
Strzepek and McCluskey (2006)	West Africa, by country	2050 & 2100	CSIRO2, HadCM3, CGCM2, ECHAM,PCM	B2, B1, A1FI, A2	Watbal	no /no/no
Manabe et al. (2004)	Niger	2050	Unknown	IS92a and 4*CO2	No name	no /no/no
Aerts et al. (2006)	Volta	2001/2099	ECBilt-CLIO-VECODE	A2	STREAM	no /no/no
Kamga (2001)	Upper Benue	2050 and 2100	HadCM2 and ECHAM4/OPYC3	IS92a, IS92e, IS92c	Yates wat. Bal.	no /no/no
Falloon and Betts (2006)	Niger	2070/2100	HadGEM1	A1B, A2	TRIP	no /no/no
van Vliet et al. (2013)	WA, Niger	2071/2100	ECHAM5/MPIOM, IPSL/CM4,CNRM/CM3	B1,A2	VIC	no /no/no
Murray et al. (2012)	Niger, Bani, Volta, Senegal, Benue, Gambia	2070/2099	CCCma CGCM3 ,CSIRO MK3.0 ,IPSL CM4 C,MPI ECHAM5 ,NCAR CCSM3.0 ,UKMO HadCM3	"2C by 2050" (all) + "4C by 2050" (only HadCm3)	LPX	no/yes/yes
Kankam-Yeboah et al. (2013)	Volta	2006/2035 2036/2075	ECHAM4/CSIRO	A1FI	SWAT	no/no/no
Aich et al. (2014)	Niger	2020/2049 & 2070/2099	HadGEM2-ES, IPSL-5 CM5A-LR, MIROC-ESM-CHEM, GFDL-ESM2M, NorESM1-M	RCP 8.5 & 2.6	SWIM	no/no/no

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

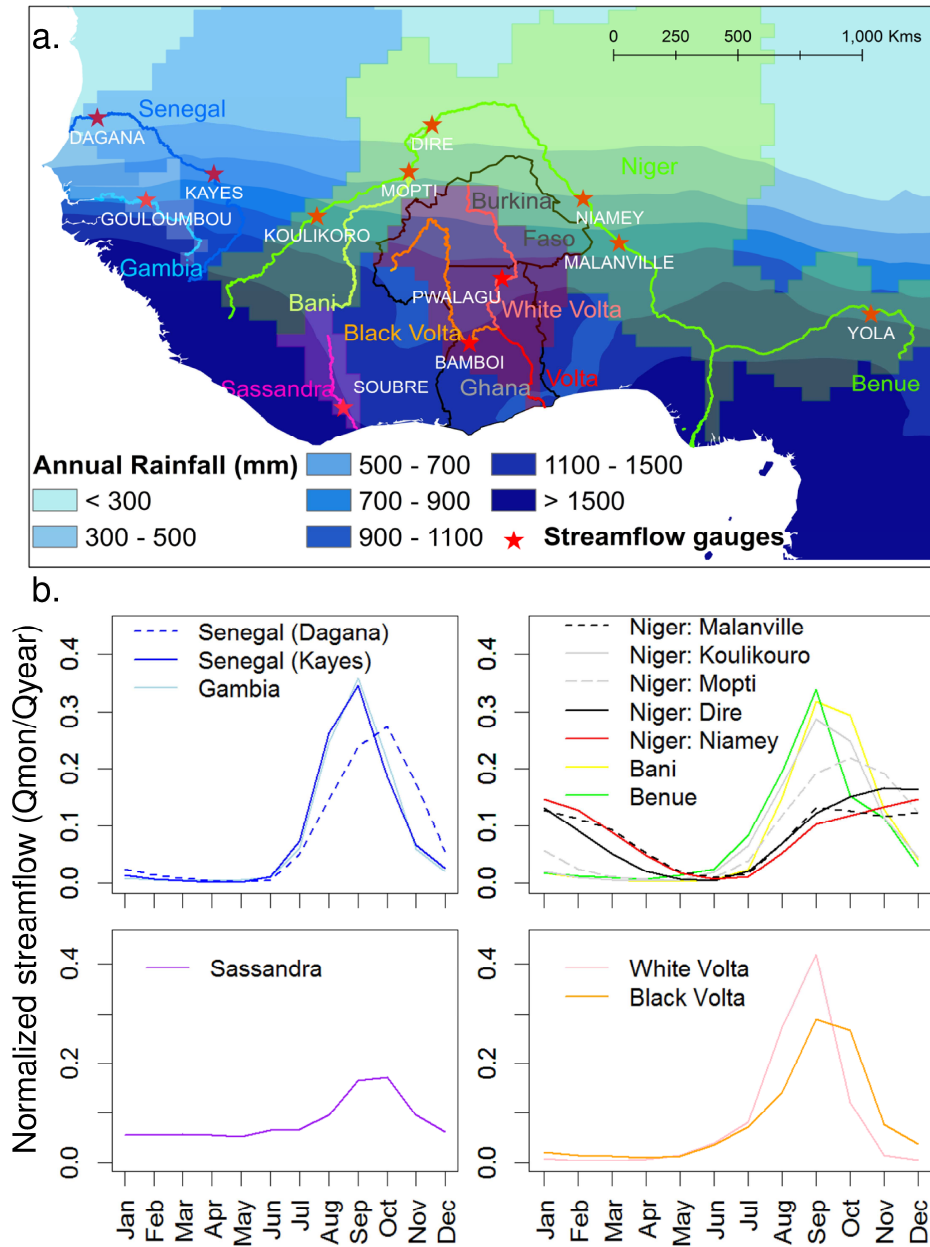
Table 3: Regression equation between rainfall change and runoff change, for each of the river.

River	Changes
Volta	<ul style="list-style-type: none"> - The magnitude of low return period (i.e., frequent) floods decreases in 2035 and 2085 in all sub-basins. For higher return period floods, it depends (McCartney et al., 2012) - Streamflow increases in Sept-Oct (around 20%), decrease in July-Aug (about -10%) ((Jung et al., 2012)) - Higher runoff values in May-June and Aug-Sept but lower in July (Kunstmann and Jung, 2005)
Senegal/Gambia	<ul style="list-style-type: none"> - At the 2080 horizon, the peak flows in September show a decrease for the Senegal (-27%) and Gambia (-37%) catchments (Ardoin-Bardin et al., 2009) - According to global maps (Murray et al., 2012), in some parts of Senegal and Gambia, the month of maximum runoff is delayed of 1 month, no strong change of minimum runoff.
Niger/Bani/Benue	<ul style="list-style-type: none"> - similar pattern (month by month) but higher peak flows in Sept-Oct and slightly lower in July-august (Kamga (2001), for Benue River) - a later occurrence of the flows and an earlier start of the depletion phase (Ruelland et al. (2012), for the Bani River) - Changes in maximum monthly river flow: A1B: +105% and A2: +137%. Peak flow is one month later for scenario A2, no change for A1B (Falloon and Betts (2006), Niger) - -1% for low flows and +11% for high flows (van Vliet et al. (2013), for the Niger River) - According to global maps (Murray et al., 2012), in the Niger delta and the Niger loop, the month of maximum runoff is 1 month delayed, no strong change of minimum runoff -For Aich et al. (2014), high flows (Q10) and especially low flows (Q90) are generally expected to increase.
Sassandra	<p>Simulated flows for June to August are greater than observed flows and partly offset the decrease in runoff in September–October in 2080 (-22%) (Ardoin-Bardin et al., 2009)</p>

Table 4: Impact of future climate on monthly runoff and on floods/droughts, according to the papers selected in the database

and detailed by rivers

1 **Figures captions**



2

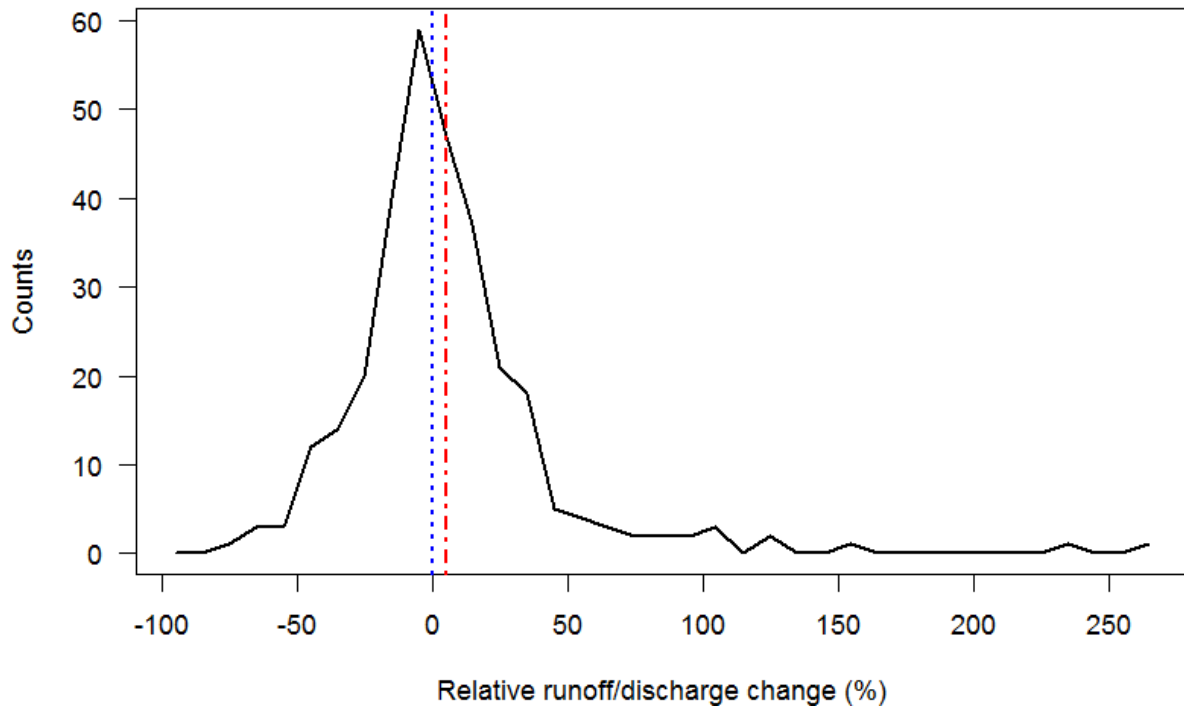
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4 Figure 1: (a) Rivers selected in this study. Rainfall values are from CRU 3.1 dataset (1970/2009) ((Mitchell and Jones, 2005).

5 Note that White Volta is also named Nakambe River. (b) Mean normalized hydrographs of the studied river basins

1 (Qmonth/Qyear). Historical data come from the Global Runoff Data Centre² (GRDC) and are for different time periods,
2 depending on the river but with at least 27 years

3



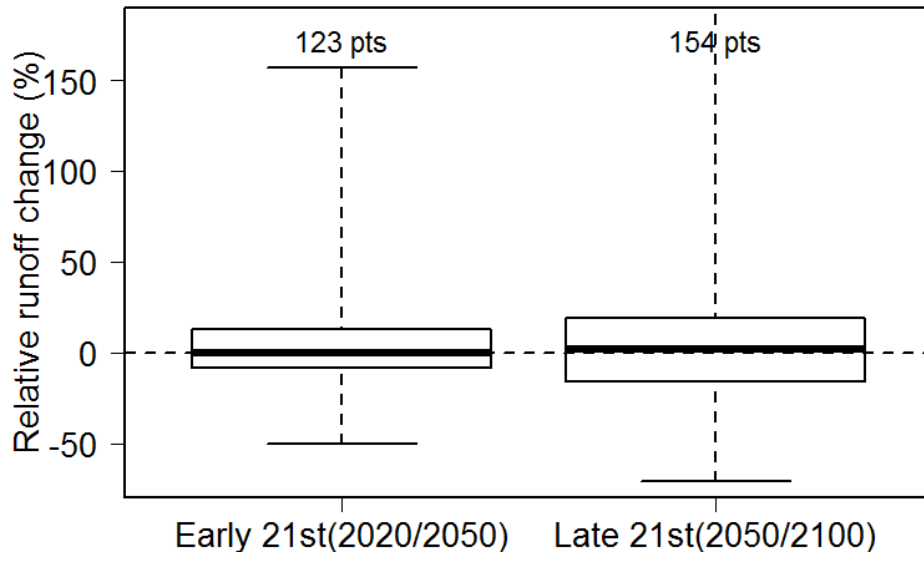
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6 Figure 2: runoff change (x axis, %) in WA based on all cases in the database (i.e., including different time period, rivers and
7 models). The blue dashed line represents the median of the distribution, the red one is the mean. We focus here only on the
8 impact of climate change: this is the only changing parameter (no water use and land use change).

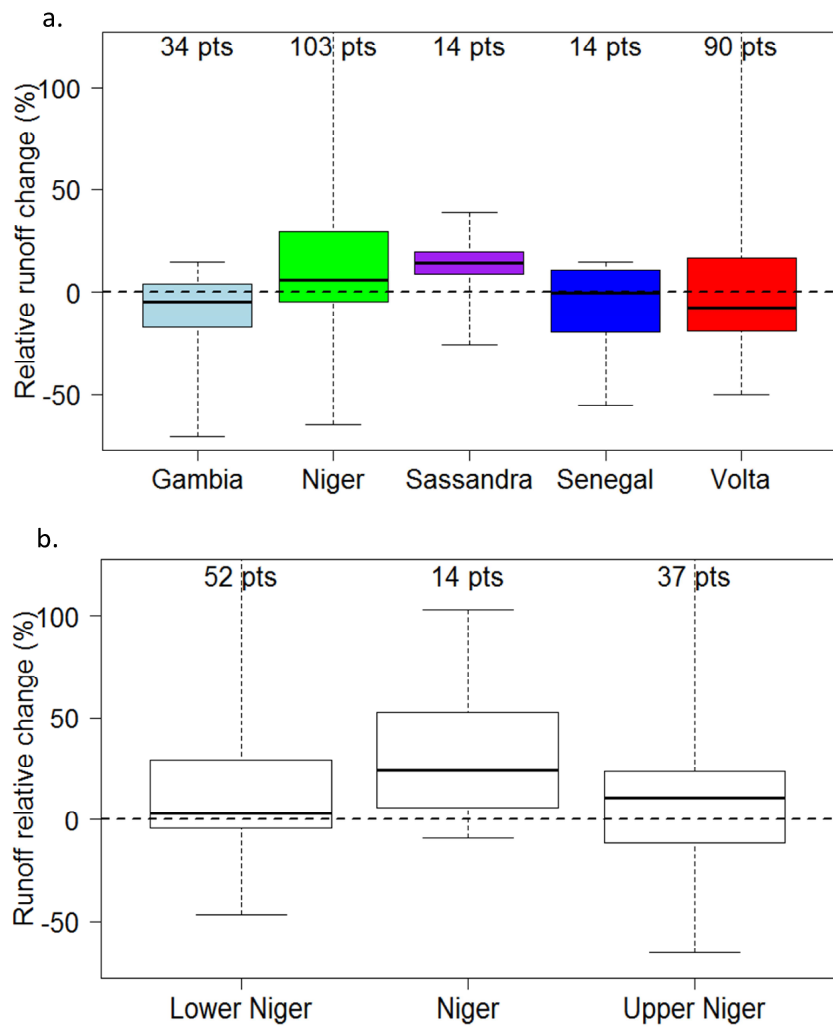
² Global Runoff Data Centre (2011): Long-Term Mean Monthly Discharges and Annual Characteristics of GRDC Station / Global Runoff Data Centre. Koblenz, Germany: Federal Institute of Hydrology (BfG), 2011.

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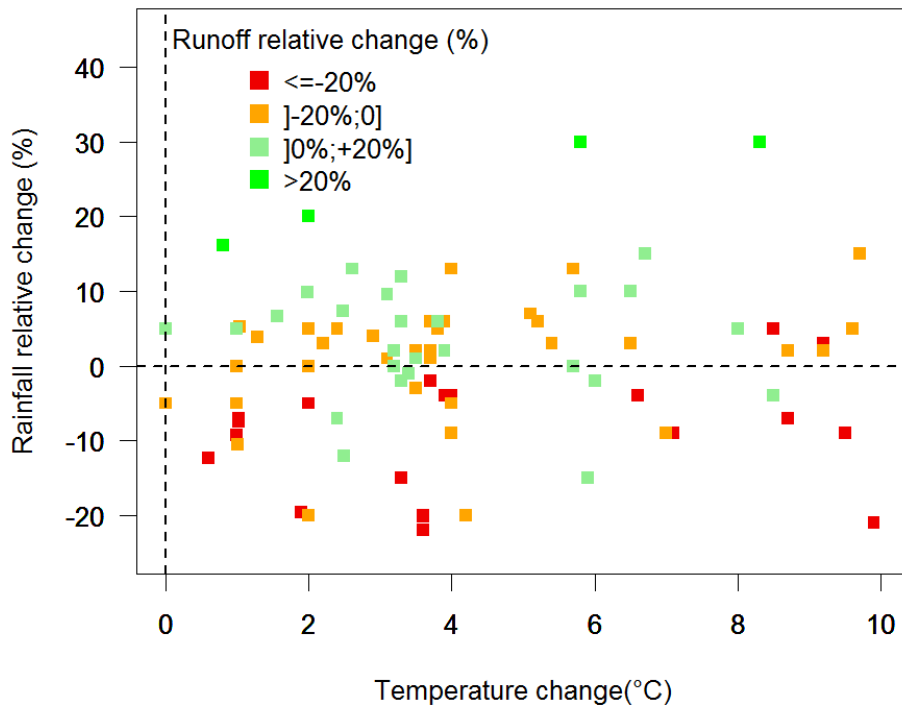
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Figure 3: Impact of climate change on runoff at the beginning of the 21st century (left, 2020-2050) and at the end (right, 2050-2100).



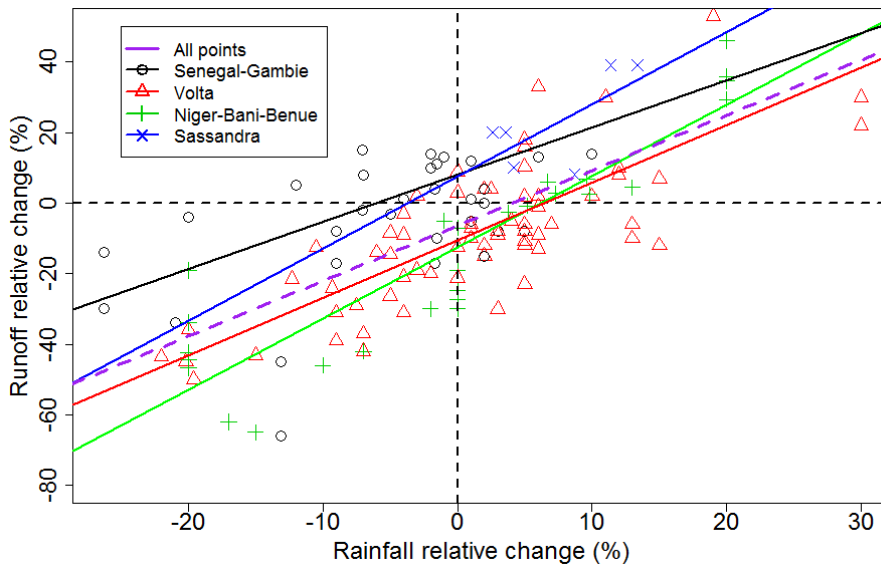
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Figure 4: (a) Impact of climate change on runoff (%), by river. Some previous clustering has been done (e.g. Bani and Benue are included with Niger and all the Volta tributaries are together) and (b) Runoff relative change (%) for different parts of river Niger, according to the database. When only Niger is specified, this means that there is no description (upper or lower Niger) in the original paper.



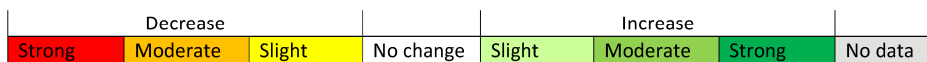
1

2 Figure 5: Rainfall (y-axis) and temperature (x-axis) anomalies associated with the runoff relative change (color scale). All the
 3 values come from the database.

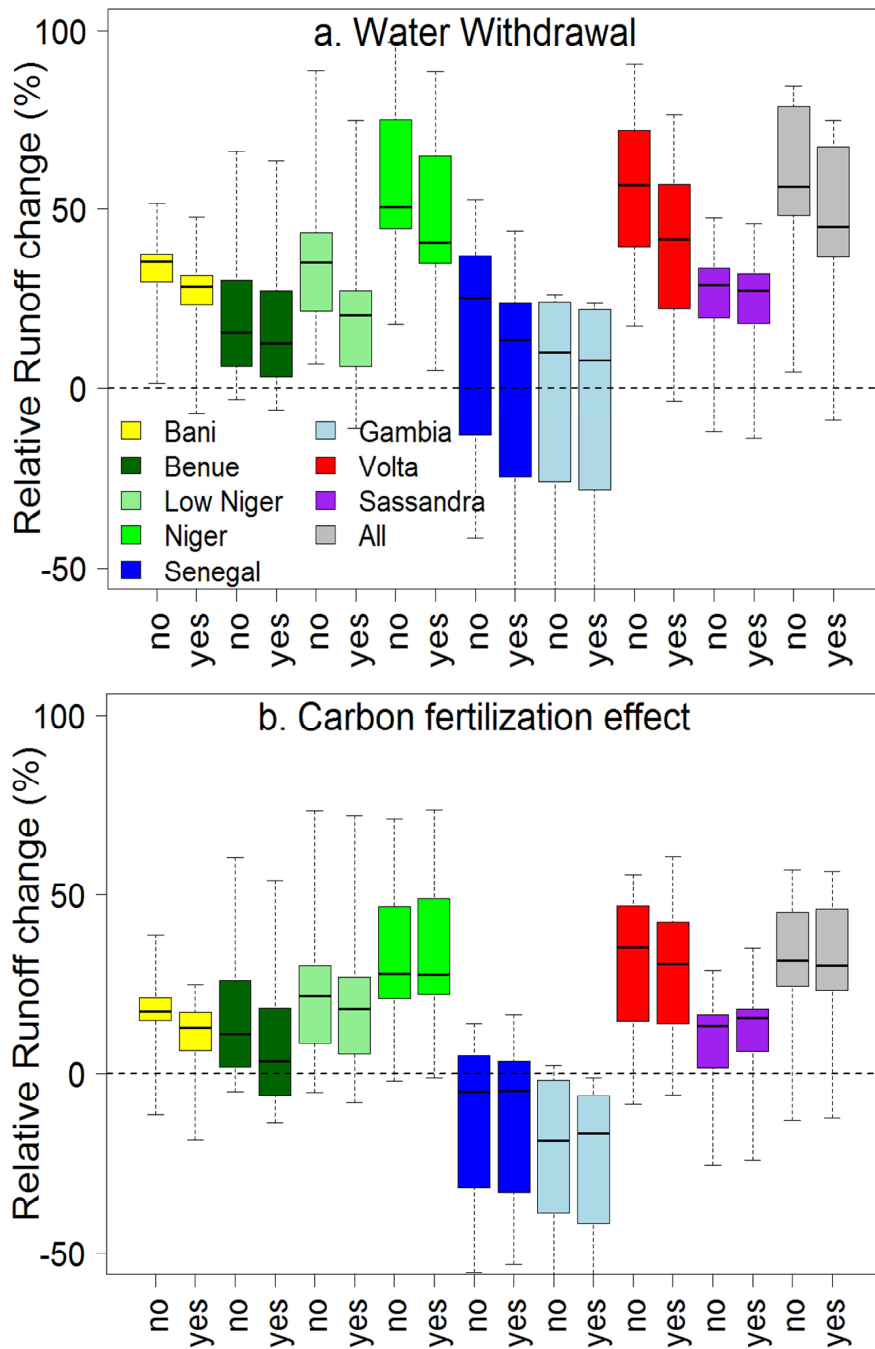


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 2 Figure 6: Relationship between runoff change (y-axis, %) and rainfall relative change (x-axis, %) for the four main rivers and for
 3 the whole panel (purple dashes). The lines represent the linear model for each river. Note that we put Senegal and Gambia
 4 altogether.

River	Paper	j	f	m	a	m	j	j	a	s	o	n	d
Volta	Jung et al. 2012												
	Kunstmann & Jung 2005												
Senegal	Ardoin-Bardin et al. 2009 (for 2080)												
	Murray et al., 2012												
Benue	Kamga, 2001, IS92c												
Bani	Ruelland et al., 2012 (HadCM3, 2055)												
Niger	Fallon & Betts, 2006												
	Van Vliet et al, 2013												
	Okpara & Perumal, 2009												
	Oguntunde & Abiodun 2012												
Lower Niger	Murray et al., 2012												
Sassandra	Ardoin-Bardin et al., 2009 (for 2080)												
Gambia	Ardoin-Bardin et al., 2009 (for 2080)												



5
 6 Figure 7: Qualitative assessment of monthly runoff relative change, for different studies of the database and for different rivers.
 7 The assessment may be an interpretation of the paper's results (see Table 4 for more details about each paper results). In some
 8 cases we only detailed here one time horizon or one climate model.



1

2 Figure 8: (a) Impact of Future water withdrawals on runoff relative change (%) for 8 rivers. "without WWD" is the scenario
 3 without water withdrawals and "with WWD" with. (b) Runoff relative change (%) for 8 rivers and 2 different scenarios: (i) taking
 4 higher carbon concentration into account ("With C") and (ii) with fixed carbon concentration ("No C"). Values are from Murray
 5 et al. (2012).