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Discussions

Climate change impacts on river discharge 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 much more 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 PET. 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. We especially underline the lack of information concerning projections of future floods and droughts, and of inter-annual fluctuations in streamflows.

1 Introduction

Surface water is fundamental for many sectors in West Africa (WA) including agriculture, power generation and fisheries. Even if most of the agriculture in the area is rainfed, some regions strongly depend on surface water. For example, the *Office du Niger* produces 40 to 50 % of rice production of Mali (Bélières et al., 2011) thanks to the Markala dam on the Niger River. Surface water collected through big dams on large rivers is also a major source of power generation in WA. The Niger River, for example, has currently a 2004 MW maximum power generation (Skinner et al., 2009) and this value could increase in the future as the power demand is dramatically increasing (+17 % year^{-1}). Finally, fisheries strongly rely on river discharge. The drought conditions occurring in WA in the 1970s and 1980s caused a drop of −50 % in fisheries production of the Niger Delta, resulting in a loss of about USD 20 million per year (Neiland and Béné, 2008).

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

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

2 Area and methodology

2.1 Area

We focus in this review on some of the main West African rivers (Fig. 1a): Niger, Volta, Senegal, Gambia and Sassandra Rivers. We did not find in the existing literature studies about other West African rivers, or they were not directly usable. WA is a region with very different climatic conditions. Its northern part is dry (between 300 and 500 mm year^{-1} for the so-called *Sahelian* area, see FAO, 2004) while the south is much wetter, with some areas receiving more than 2000 mm year^{-1}. In the part where annual precipitation is below 1100 mm year^{-1}, encompassing the *Sahelian*, *Sudano–Sahelian* (500–900 mm year^{-1}) and *Sudanian* areas (900–1100 mm year^{-1}), rainfall occurs during a single rainy season whose core months are July, August and September which is caused by the shift of the Intertropical Convergence Zone (ITCZ) to the north (Sultan, 2002). In the southernmost area, called *Guinean* (> 1100 mm year^{-1}) there are two rainy periods, namely the short one ranging from September to November and the long one, from March to July, that are occurring at each passage of the ITCZ. The variations in seasonal pattern of rainfall lead to strong interannual streamflow fluctuations. Figure 1b shows the average hydrographs for the selected rivers, based on the rescaled flow ($Q_{\text{month}}/Q_{\text{year}}$). They underline the differences among rivers (e.g. Niger vs. Senegal) but also within a river basin. The latter is because the drainage basins of some rivers in WA can be very large, especially for the Niger (circa 2.1×10^6 km^2), and as a consequence includes strongly contrasted climatic and agro-ecological regions. The Upper Niger River hydrograph (Mopti, Koulikouro, Bani River), for example, depicts a much sharper high flow peak than its downstream counterpart (Niamey, Malanville, Dire) because of the size of the basin, and because of the inner delta, where peak discharge is strongly attenuated by flooding and evaporation. This is also expressed by the time of occurrence of high flows, which is in September–October for the upstream Niger reaches, and December–January for the more downstream ones.

2.2 Factors influencing runoff

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

- *Climate variability and change*: several studies have shown that discharge evolutions over the past decades in WA have been strongly affected by rainfall variations. After the wet 1950s and 1960s, a strong rainfall deficit happened since 1970 in the Sahelian and Sudano–Sahelian areas (e.g. Paturel et al., 2003) with some dramatic droughts like the 1973/1974 and 1983/1984 ones. Recent studies such as Lebel and Ali (2009), however, suggest a recovery of the rain in eastern parts of WA, whereas drought conditions endure in western regions. These rainfall variations have led to strong fluctuations in river discharge with a general negative trend from 1960 to 2010 (Descroix et al., 2013), especially in Sudanian areas. In Guinean areas the decrease has been more moderate. Mahe et al. (2013) underlined the non-linear effect of this rainfall drop over much of WA, with a −20 % decrease in rainfall resulting in a decrease of −60 % in runoff.

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

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

- *Changes in water consumption/withdrawals*: this factor may have an important impact on runoff in a region where the population is growing fast. For example, in WA water withdrawals have increased by 31 % between 1983/1987 and 1998/2002 (Aquastat[1]). This value could increase much more in the future as food demand could quintuple by 2050 in the region (Collomb, 1999).

- *Carbon effect*: rising CO_2 concentration could alter vegetation water use (and thus the water cycle) through two opposite effects (Tubiello et al., 2007; Leakey, 2009; Alkama et al., 2010): (i) lower stomatal conductance which leads to a reduction in potential evapotranspiration (PET) and (ii) enhanced photosynthesis which leads to an increase in Leaf Area Index and an increase in PET. Even though the effects of increased atmospheric CO_2 levels on discharge remains highly uncertain, some global studies like Gerten et al. (2008) and Shi et al. (2011) have demonstrated that this carbon effect may have had a non-negligible impact on runoff.

2.3 Database

We collected all studies that have evaluated the effects of these major drivers on future runoff regimes in WA. Most studies have focused on the effects of climate variables

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

changes. We constructed a database storing results of this latter effect. For this ensemble of projections, representing a wide variety of models, scenarios and methodologies, we quantify changes in runoff characteristics and the uncertainty therein. On the other hand, only few studies have addressed the other drivers of runoff change: therefore, results from these papers are not included in the database and are summarized herein in a more qualitative manner. To create the database, we followed a methodology close to Roudier et al. (2011): we selected 19 peer-reviewed papers, Ph.D thesis or official reports published since 2000 that focus on runoff/discharge changes in WA (ECOWAS countries + Cameroon) in view of climate change (Table 1). Milly et al. (2005) and Arnell (2004) were excluded from the database because it was not possible to access the detailed results at the river or regional scale or because they do not focus on the selected variables. These studies were however used in the discussion. The final database includes 301 runoff change values defined by different rivers, climate models, emission scenarios, time horizons and hydrological models. Most studies used climate variables directly from climate models that were forced by future greenhouse-gases emission scenarios like the SRES (Special Report on Emission Scenario, see Arnell, 2004 for a description) or RCPs (Representative Concentration Pathways, Moss et al., 2010). These climate variables were then used as inputs in an offline hydrological model (e.g. Falloon and Betts, 2006; Kamga, 2001). Some studies however did not use directly these climate models but made some assumptions about the future climate to generate potential time series (e.g. +2 °C and −5 % for rainfall, Okpara and Perumal, 2009). Since such scenarios are within the range of potential evolutions simulated by the GCMs, we decided to include them in the database.

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

Concerning the other drivers of runoff change, McCartney et al. (2012) and Murray et al. (2012) used scenarios of water use change, Murray et al. (2012) dealt with the effects of increased atmospheric carbon concentration on runoff, and no study accounted for land use dynamics. Note that to be consistent with the other studies dealing only with climate change, we did not use the results including water use and land use changes in Sects. 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 Sect. 3.4.

3 Results

3.1 Impact of climate change on yearly mean discharge

3.1.1 Over the whole region

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

The studies that were not contained in the database for reasons previously discussed do not agree either on the sign of runoff change in WA. Milly et al. (2005) found a slight negative trend and Paturel et al. (2007) concluded on a much more negative one, largely due to the use of a quite pessimistic scenario (PET +5 %; Rainfall −10 %, $2 \cdot CO_2$). On the other hand, Arnell (2004) found that by 2055 in WA much less people would be affected by water stress, whereas Faramarzi et al. (2013) projected no change or a small increase in surface water and groundwater availability in most of West African countries.

Figure 2 focuses on all points in the database, hereby mixing projections across different time horizons. To evaluate if the predicted impacts may be more pronounced by the end of the 21st century because of rising greenhouse gases concentrations we split the database in two parts based on the time horizon studied: early 21st century (2020–2060) and late 21st (2061–2100). Figure 3 shows that the selected future time period does not strongly influence the overall sign of future runoff evolution: the median for the early 21st century is indeed 0 and +2 % for the late 21st century, but the difference is not significant. It is however important to note that both panels (early and late) do not include the same rivers, models or scenarios. The increase in interquartile range as time proceeds nevertheless suggests that signals of change become more pronounced with increasing greenhouse gas levels. This is also confirmed when evaluating the projections of individual studies that consider different time horizons. In 68 % of the cases, the impact of climate is more evident in the late 21st, especially when the emission scenario taken into account has very contrasted radiative forcing between late and mid-century. Ruelland et al. (2012), for example, project a runoff evolution of −5 % by 2025 and −65 % by 2085, using the SRES A2 scenario.

3.1.2 Impact by river

To evaluate projections in different regions of WA we clustered river basins or areas under the following labels: Niger is: Niger, Bani and Benue; Volta is: White Volta (or Nakambe), Black Volta, Burkina Faso (country using results of Strzepek and McCluskey, 2006) and Ghana (country). For the Senegal and Volta Rivers, Fig. 4a shows that the median change is not statistically different from 0, which means that the impact of climate change is small or not clear, even if it could potentially be very strong in some cases. For the Gambia River a small but significant negative trend is projected (median = −4.5 %), whereas a positive significant evolution in river flows is projected for the Sassandra (+14.4 %) and the Niger River (+6.1 %). It is however important to note that the positive trend for the Niger River is mainly due to Aich et al. (2013), which represent 40 % of the selected runoff changes.

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

3.2 Relative role of rainfall and temperature in discharge evolution

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

To analyze the elasticity of runoff to precipitation (Guimberteau et al., 2013) in different parts of WA, we plot in Fig. 6 the future changes in runoff vs. those in rainfall for the four main rivers and for the whole area. The variation in steepness of the fitted linear regression lines shows that rivers in WA react differently to the same drop or increase in rainfall. The highest sensitivity to rainfall changes is found in the Niger and Sassandra,

although for the latter basin data points are only available for positive changes in precipitation. Aich et al. (2013), doing the same kind of analysis for the Niger but with annual values found an even stronger sensitivity to rainfall: according to their study, a +25 % increase in rainfall would lead to +90 % increase in runoff. The lowest sensitivity is found for Senegal/Gambia, but the underlying values come from only one study. The fitted lines do not intersect the y axis at zero but at different points along the y axis. If so, this would imply no change in river runoff for no change in rainfall. Here, however, this shift is related to catchment-specific sensitivities of runoff to changes in PET and T as well as to uncertainties in the hydrological model in translating climate inputs to runoff. These effects that are not caused by rainfall changes seem strongest for the Niger and Volta rivers (circa −12 %, close to Aich et al., 2013, for the Niger River). Their overall impact is about −8 % taking all rivers and warming scenarios into account, and a 10 % drop in rainfall would result in a reduction in river flow of approximately 25 %.

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

Most studies contained in the database focus solely on annual discharges. Some studies, however, also detailed the impacts of future climate on monthly values and extreme river flows. We summarized the results for each river and present a qualitative assessment in Fig. 7 and Table 2. To date, only McCartney et al. (2012) has focused in WA on the potential effect of climate change on the magnitude of floods for a range of return periods. By the end of this century, the magnitude of frequent floods (with return periods less than 10 years) is projected to decrease in the Volta River, whereas the trend for higher return periods (or more extreme) floods is not consistent from station to station. Moreover, Jung et al. (2012) and Kunstmann and Jung (2005) found an increase in runoff in September when flows in the Volta are typically the highest (see Fig. 1a). For the Senegal, Gambia and Sassandra Rivers, on the other hand, high flows (September and October) are projected to decrease (Ardoin-Bardin et al., 2009). On the Niger River, results depend on the area studied but some agreements seem to arise on (i) a later occurrence of the peak flows (Murray et al., 2012; Falloon and

Betts, 2006) and (ii) an increase of peak flows (Kamga, 2001; van Vliet et al., 2013; Falloon and Betts, 2006). However, this is only a global pattern. As underlined by Aich et al. (2013), the results strongly depend on the climate model used and also on the area. On the Bani River which is a tributary of the Niger, Ruelland et al. (2012) found indeed a strong decrease in maximum monthly runoff. These findings show that there is currently insufficient information to make strong statements about possible evolutions in West African hydrographs, although any such changes would be a major concern for flood protection, dam design or socio-economic activities depending on water availability (Roudier and Mahé, 2010).

3.4 Impact of climate change vs. other factors

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

3.4.1 Carbon effect and water consumption

McCartney et al. (2012) designed four different scenarios of water consumption whereas Murray et al. (2012) accounted for the effects of water withdrawals and of atmospheric carbon increase. Both studies underlined the potential of these drivers in altering streamflows but the changes they induce are generally less important than the effects of climate change. McCartney et al. (2012) found an average impact of climate change on runoff of −34 % without water use changes and −43 % with the

full development scenario. Similarly, Fig. 8a, which summarizes the results of Murray et al. (2012), shows that the effects of water withdrawals on future runoff can be considerable but do not reverse the climate signal. Moreover, the effect of carbon on runoff depicted in Fig. 8b seems to be smaller than that of water withdrawal changes. In WA as a whole, the median change under the scenario with fixed carbon concentration amounts to +31.6 % while a +30.3 % increase in runoff is projected when the increase in carbon concentration is accounted for. However, as underlined by Murray et al. (2012), the effect of higher carbon concentration on runoff is very different across WA: it can indeed cause a decrease (e.g. Benue River) or an increase (Sassandra) in river discharge. These results are coherent with past trends at the global scale on the relative share of land use, water consumption/withdrawal, climate and carbon effect on retrospective runoff changes (Sterling et al., 2013).

3.4.2 Land use changes

Gerbaux et al. (2009) for the Sahelian area and Sterling et al. (2013) at the global scale have demonstrated that anthropogenic land use dynamics have been more or equally important as climate change in past runoff evolution. These studies illustrate the very important role of land use changes on hydrology. Despite this potential strong impact, we found only three studies that we did not include in the database dealing with this issue. Oguntunde et al. (2012) showed that for different hypothetical levels of reforestation in the Niger basin the runoff increases up to +25 %. Meigh et al. (2005), on the other hand, found almost no change when including land use in their analysis in WA. Finally, Cornelissen et al. (2013), using several contrasted scenarios of future land use changes in Benin found that such modifications could have a substantial impact on discharge. However, it strongly depends on the hydrological model used. Further studies using socio-economic based land use change scenarios are thus needed in order to assess precisely the role of land use in future discharge changes in WA.

4 Conclusion

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

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

This review shows the need for more studies on the assessment of future water resources in WA. Despite the general agreement about the high vulnerability of WA to climate change, there is a real lack of studies focusing on this area. Future studies should look more in detail to high and low flow variations which are fundamental for agriculture, fisheries and dams. 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.

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Table 1. Studies selected in the database.

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 $4 \cdot CO_2$	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. (2013)	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

Table 2. Impact of future climate on monthly runoff and on floods/droughts, according to the papers selected in the database and detailed by rivers.

River	Changes
Volta	– 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 Jul–Aug (about −10 %) (Jung et al., 2012) – Higher runoff values in May–Jun and Aug–Sept but lower in Jul (Kunstmann and Jung, 2005)
Senegal/Gambia	– At the 2080 horizon, the peak flows in Sep 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	– similar pattern (month by month) but higher peak flows in Sept–Oct and slightly lower in Jul–Aug (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. (2013), high flows (Q10) and especially low flows (Q90) are generally expected to increase.
Sassandra	– Simulated flows for Jun to Aug are greater than observed flows and partly offset the decrease in runoff in Sep–Oct in 2080 (−22 %) (Ardoin-Bardin et al., 2009)

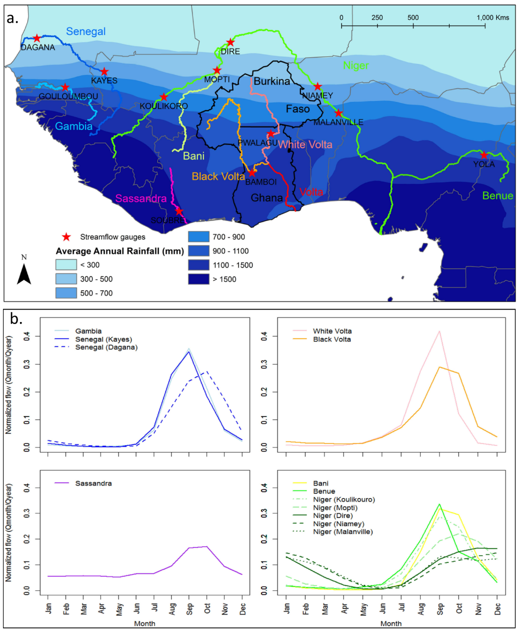

Fig. 1. (a) Rivers selected in this study. Rainfall values are from CRU 3.1 dataset (1970/2009) (Mitchell and Jones, 2005). Note that White Volta is also named Nakambe River. **(b)** Mean normalized hydrographs of the studied river basins ($Q_{\text{month}}/Q_{\text{year}}$). Historical data come from the Global Runoff Data Centre[2] (GRDC) and are for different time periods, depending on the river but with at least 27 years.

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

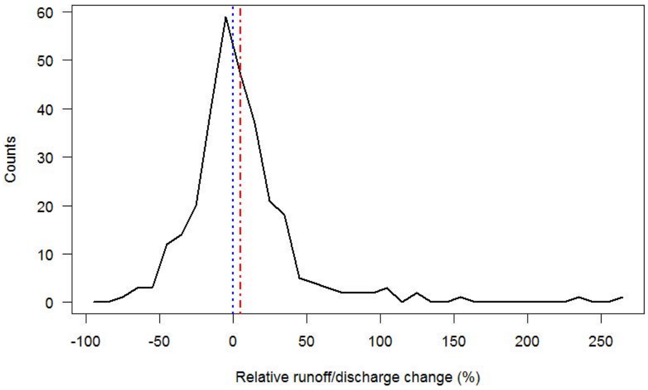

Fig. 2. Runoff change (x axis, %) in WA based on all cases in the database (i.e. including different time period, rivers and models). The blue dashed line represents the median of the distribution, the red one is the mean. We focus here only on the impact of climate change: this is the only changing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

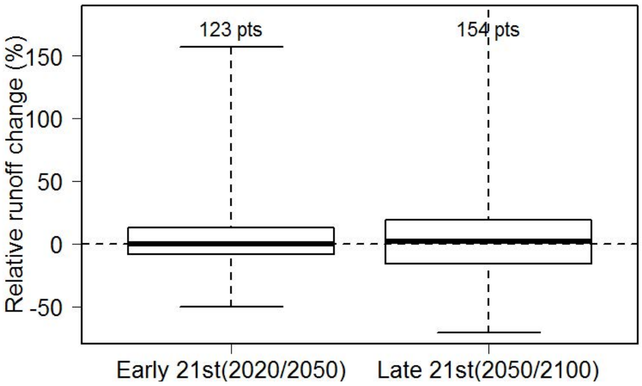

Fig. 3. Impact of climate change on runoff at the beginning of the 21st century (left, 2020–2050) and at the end (right, 2050–2100).

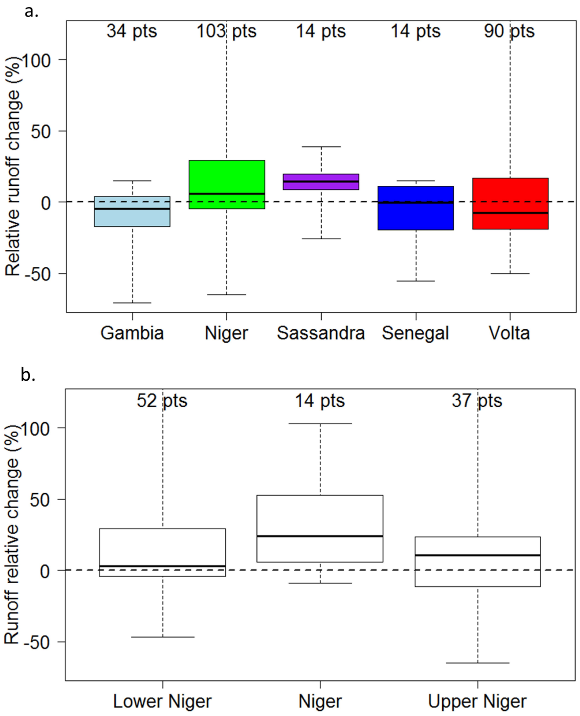

Fig. 4. (a) Impact of climate change on runoff (%), by river. Some previous clustering has been done (e.g. Bani and Benue are included with Niger and all the Volta tributaries are together) and **(b)** runoff relative change (%) for different parts of river Niger, according to the database.

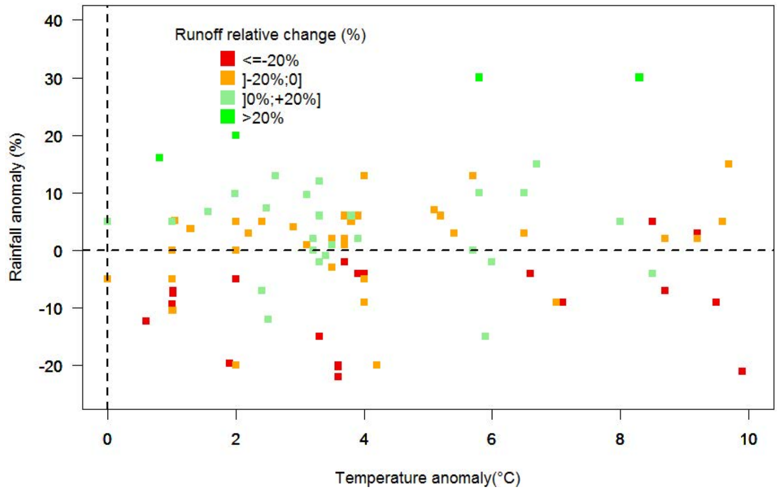

Fig. 5. Rainfall (*y* axis) and temperature (*x* axis) anomalies associated with the runoff relative change (color scale). All the values come from the database.

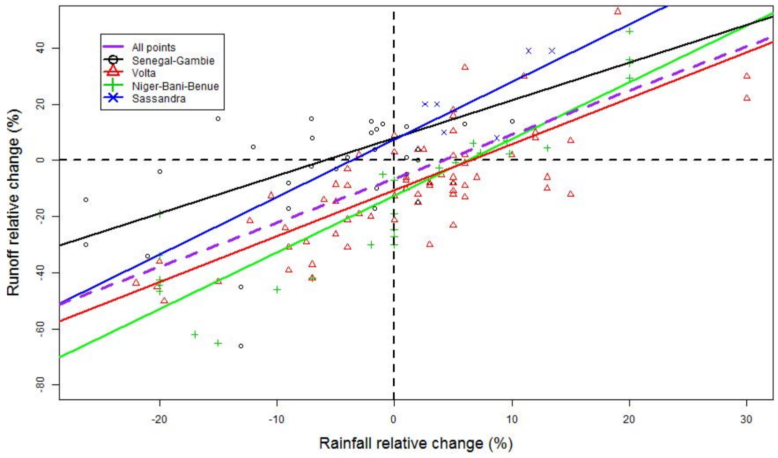

Fig. 6. Relationship between runoff change (*y* axis, %) and rainfall relative change (*x* axis, %) for the four main rivers and for the whole panel (purple dashes). The lines represent the linear model for each river. Note that we put Senegal and Gambia altogether.

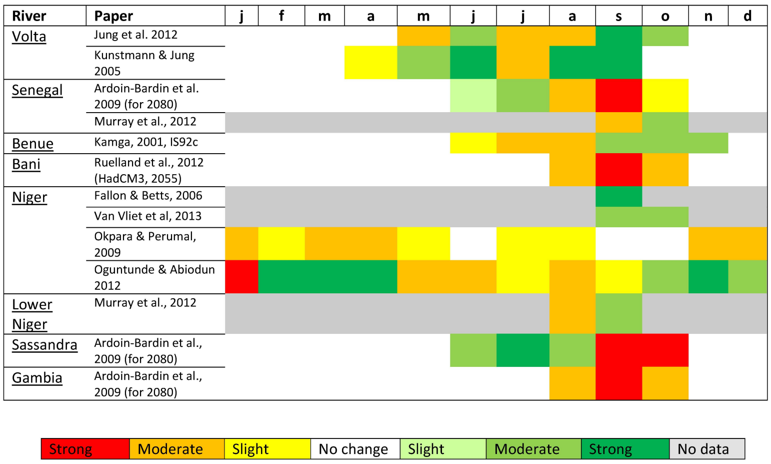

Fig. 7. Qualitative assessment of monthly runoff relative change, for different studies of the database and for different rivers. The assessment may be an interpretation of the paper's results (see Table 2 for more details about each paper results). In some cases we only detailed here one time horizon or one climate model.

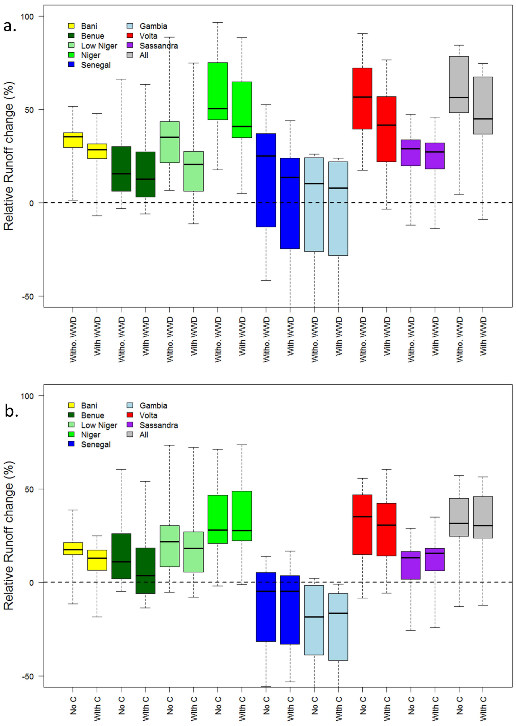

Fig. 8. (a) Impact of Future water withdrawals on runoff relative change (%) for 8 rivers. "without WWD" is the scenario without water withdrawals and "with WWD" with. **(b)** Runoff relative change (%) for 8 rivers and 2 different scenarios: (i) taking higher carbon concentration into account ("With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