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WASCAL
West African Science Service Center on Climate Change and Adapted Land Use

# CLIMATE CHANGE IN THE NIGER BASIN ON HYDROLOGICAL PROPERTIES AND FUNCTIONS OF KAINJI LAKE, WEST AFRICA

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## DEDICATION

To the Prophet of Allah, Mohammed (SAW), my father Alhaji Olalekan Oyerinde, my mother Alhaja Folashade M. Oyerinde and the entire family.

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## LIST OF ABBREVIATIONS

| | |
|---|---|
| ARMAX | Auto-Regressive, Moving Average, With Exogenous Inputs |
| ASECNA | *Agence pour la Securite de la Navigation Aerienne en Afrique et a Madagascar (ASECNA)* |
| BMBF | German Ministry of Education and Research |
| CMIP5 | Coupled Model Intercomparison Project Phase 5 |
| CORDEX | Coordinated Regional Downscaling Experiment |
| DJF | December-January-February |
| *ESGF* | *Earth System Grid Federation* |
| GCM | Global Climate Model |
| GIS | Geographic information systems |
| GPCP | The Global Precipitation Climatology Project |
| HYDROMAD | Hydrological Model Assesement and Development Group |
| IHACRES | Identification of Unit Hydrographs and Component Flows from Rainfall, Evaporation and Streamflow Data |
| IPCC | Intergovernmental Expert Panel on Climate Change |

| | |
|---|---|
| ITCZ | Intertropical Convergence Zone |
| JJA | June-July-August |
| LAM | Limited Area Models |
| MAM | March-April-May |
| MERRA | Modern Era Retrospective-analysis for Research and Applications |
| PET | Potential Evapotranspiration |
| RCM | Regional Climate Model |
| RCP | Reference Concentration Pathways |
| SMHI | *Sveriges Meteorologiskaoch Hydrologiska institute* |
| SON | September-October-November |
| UNEP | United Nations Environment Programme |
| USD | US Dollars |
| WASCAL | West African Science Service Center on Climate Change and Adapted Land Use |
| WCRP | World Climate Research Program |

| | |
|---|---|
| NSE | Nash-Sutcliffe Efficiency |
| d | Index of Agreement |
| md | Modified Index of Agreement |
| r | Pearson Correlation coefficient |
| $R^2$ | Coefficient of Determination |
| KGE | Kling-Gupta Efficiency |

## RÉSUMÉ

Le bassin du fleuve Niger où habitent plus de 100 millions de personnes, est un bien vital et complexe pour l'Afrique de l'Ouest. Depuis les années 1970, le bassin a été caractérisé par des changements hydro-climatiques avec des impacts significatifs sur les ressources en eau. Le changement climatique pourrait avoir de grands impacts sur la disponibilité de l'eau dans le bassin, mais sa simulation efficace est entravée par le nombre insuffisant et la diminution de stations d'observation fiables. Les modèles climatiques existants ont du mal à bien simuler le climat du bassin en raison de la complexité et de la diversité des processus caractérisant le bassin. Aucune tendance uniforme n'a émergé des sorties des modèles de circulation générale (MCG), soit pour une diminution ou une augmentation des précipitations. Les pays du bassin du fleuve Niger (Afrique de l'Ouest) prévoient d'investir des millions de dollars dans l'expansion de l'hydroélectricité dans le futur proche. Avec les impacts du changement climatique dans le bassin se produisant déjà, il est nécessaire de comprendre l'influence des changements hydro-climatiques futurs sur les ressources en eau et sur la production d'énergie hydroélectrique dans le bassin. Cette thèse intègre les opinions des populations locales et l'approche scientifique dans l'évaluation des impacts du changement climatique sur les ressources en eau dans le bassin du Niger. La cohérence des perceptions locales et des réponses adaptatives aux précipitations et

aux débits observés du fleuve a été évaluée dans le bassin du Niger. Des données socio-économiques ont été recueillies auprès de 239 ménages dans 30 communautés à travers deux localités (Malanville et Kainji) dans le bassin du Niger. Les données historiques sur les précipitations et sur les débits du fleuve de 1950-2010 ont été analysées et leur accord avec les perceptions locales a été évalué. Les tendances climatiques futures ont été évaluées avec 8 MCG et deux scénarios d'émissions (RCP4.5 et RCP8.5) dans le cadre du projet de désagrégation spatiale climatique a l'échelle régionale (CORDEX - CMIP5). Les tendances futures (2010-2100) et l'influence de la correction de biais sur les sorties des 8 MCG ont également été évaluées. Par ailleurs, un modèle hydrologique a été adapté et utilisé pour évaluer les impacts du changement climatique sur le ruissellement dans les conditions actuelles et futures. Pour déterminer les impacts du changement climatique sur la production d'énergie hydroélectrique, un modèle hydro-électrique basé sur des observations au niveau du plus grand barrage hydroélectrique (Kainji) dans le bassin du Niger a été développé. Il y avait un accord entre les observations et les perceptions. Les résultats de cette thèse montrent une bonne indication des secteurs les plus vulnérables ainsi que les communautés qui ont affiché la plus grande volonté de lutter contre le changement climatique. Le changement climatique va entrainer environ 5-10% d'augmentation des précipitations avec une grande variabilité spatiale dans le bassin du Niger. La partie sahélienne aura en grande partie cette augmentation des précipitations. L’accord de modèles globaux sur les précipitations projetées montre une grande confiance du projet CMIP5 dans le régime des précipitations dans le bassin du Niger. La correction des biais a amélioré la qualité des projections de précipitations des 8 MCG en reproduisant bien les précipitations observées. Des moyennes de 0,74 (NSE), 0,92 (d), 0,80 (md), 0,89 (r), 0,79 (R2) et 0,76 (KGE) ont été trouvées par comparaison climatologique entre les 8 MCG et les données de précipitations observées par satellite avant la correction des biais tandis que des moyennes de 0,86 (NSE), 0,97 (d), 0,86 (md), 0,93 (r), 0,87 ($R^2$) et 0,92 (KGE) ont été constatées après la correction des biais. Le modèle hydrologique IHACRES amélioré et présenté dans cette thèse, a montré une grande aptitude pour le bassin en raison des coefficients de performance trouvés in collage du modèle (0,73 (NSE), 0,92 (d), 0,74 (md), 0,85 (r), 0,73 ($R^2$) et 0,81 (KGE)). Le changement climatique va entrainer une augmentation des précipitations, de la température, de l’evapotranspiration potentielle sur le bassin du Niger et du ruissellement à Kainji et Malanville. L’accord des 8 GCM sur l'augmentation du ruissellement projeté pour le modèle hydrologique dans le bassin montre une grande confiance de la modélisation présentée dans cette étude. Le modèle hydro-électrique développé, montre de grands coefficients d'efficacité in collage (0,81 (NSE), 0,94 (d), 0,81 (md), 0,95 (R), 0.90 (R2) et 0,75 (KGE)) entre les niveaux d’eau observés et

simulés à Kainji ; ceci montre un grand potentiel pour son applicabilité dans le bassin. Le changement climatique va entrainer environ 50 MW (RCP4.5) et 100 MW (RCP8.5) d'augmentation moyenne annuelle de la production d'énergie hydroélectrique dans le bassin du Niger. Ce potentiel pourrait être exploité positivement par extension du stockage de l'eau pour la production hydroélectrique dans certaines parties du bassin où il y aura une augmentation significative du débit comme il a été trouvé en amont du lac Kainji.

**Mots clés :** Changement climatique, débit, énergie, Kainji, Niger bassin.

# ABSTRACT

The Niger River Basin - home to over 100 million people - is a vital and complex asset for West Africa. Since the 1970s, the basin has been characterized by hydro-climatic changes with significant impacts on water resources. Climate change could potentially have large impacts on water availability in the basin, but its effective simulation is hampered by inadequate and diminishing number of reliable observation stations. Climate simulations in the basin have also been difficult to handle with existing models due to the complexity and diversity of processes to be represented. No consistent trend for either decreasing or increasing precipitation emerged from global climate model (GCM) products. Countries in the Niger River basin (West Africa) are planning to invest millions of dollars in the expansion of hydropower in the nearest future. With the impacts of climate change in the basin already occurring, there is a need to comprehend the influence of future hydro-climatic changes on water resources and hydro-power generation in the basin. This thesis integrates opinions of local populations with scientific approach in the evaluation of impacts of climate change on water resources in the Niger basin.

The consistency of indigenous perceptions and adaptive responses to rainfall and river discharge observations was evaluated in the Niger Basin. Socioeconomic data were collected from 239 households in 30 communities across two settlements in

the Niger basin. Historical data on rainfall and river discharge from 1950-2010 were analyzed and agreement with local perceptions assessed. Future climate trends were assessed with 8 GCMs and two emission scenarios (RCP4.5 and RCP8.5) from the Coordinated Regional Downscaling Experiment (CORDEX - CMIP5) framework. Future trends (2010-2100) and influence of bias correction on projected climate patterns from the 8 GCMs were also evaluated. Consequently, a hydrological model was adapted and used to evaluate impacts of climate change on runoff under present and future conditions. To determine impacts of climate change on hydropower production, a hydro electricity model based on gauged observations from the largest hydroelectricity dam (Kainji) in the Niger basin was developed. There was close agreement between observations and perceptions.

Indigenous perceptions gave good indication of the most vulnerable sectors as well as communities who displayed the greatest willingness to combat climate change. Climate change will drive about 5-10% ensemble median increase in precipitation with high spatial variability in the Niger basin. Larger parts of this increase in precipitation will be experienced in the Sahelian region. Close GCM agreement on projected precipitation pattern shows great confidence in the CMIP5 projected precipitation pattern across the Niger basin. Bias correction improved the quality of rainfall projections from the 8 GCMs by improving their fitness to the observed. Means of 0.74(NSE), 0.92(d), 0.80 (md), 0.89(r), 0.79(R2) and

0.76(KGE) were recorded for climatological comparison between GCMs and satellite modeled observed precipitation before bias correction while means of 0.86(NSE), 0.97(d), 0.86 (md), 0.93(r), 0.87(R2) and 0.92(KGE) were witnessed after bias correction. The improved IHACRES hydrological model presented in this thesis showed high suitability for the basin based on recorded high calibration (0.73(NSE), 0.92(d), 0.74 (md), 0.85(r), 0.73(R2) and 0.81(KGE)) efficiency coefficients. Climate change will drive increase in precipitation, temperature, PET on the Niger basin and runoff at Kainji and Malanville. Close GCM agreement on projected increasing runoff pattern in the basin shows great confidence in the modeling framework presented in this study. The invented hydropower model displayed high calibration (0.81(NSE), 0.94(d), 0.81 (md), 0.95(r), 0.90(R2) and 0.75(KGE)) efficiency coefficients between observed and simulated Kainji lake reservoir level which gives great potential for its applicability in the basin. Climate change will drive about 50MW (RCP4.5) and 100MW (RCP8.5) ensemble median annual average increase in hydropower production in the Niger basin. This potential could be positively exploited by expanding water storage for hydropower production, in parts of the basin where there will be significant increase in discharge as witnessed upstream the Kainji lake.

**Keywords :** Climate change, energy, Kainji, Niger basin, runoff.

# Table of Contents

# List of Tables

# List of Figures

# CHAPTER 1

## General Introduction

The issues of climate variability and climate change have been at the centre of many scientific studies. The 20th Century has been reported as the warmest the world has seen in 1,000 years, and the 1980s and 1990s were the hottest decades on record (Soon et al. 2003). An analysis of temperature records shows that the earth has warmed an average of $0.6^0C$ over the past 100 years (IPCC 2007). The warming is real and significant though its intensity has varied from decade to decade, from region to region and from season to season, and is mainly caused by carbon dioxide ($CO_2$) and other greenhouse gases (Crosson 1997). Climate variability and climate change have also been found to be deeply rooted in West Africa. The 1930-1960 wet periods, the 1970-1980 droughts and the return of rainfall in the 1990s and 2000s illustrate this clearly and have demonstrated the population's vulnerability, particularly in the Sahel zone (Writeshop 2007). This vulnerability may be attributed to low incomes, low technological and institutional capacity to adapt to rapid changes in the environment, as well as to their greater reliance on climate-sensitive renewable natural resources sectors such as water and agriculture.

Renewable freshwater resources have been shown by climate projections and observational records to be highly vulnerable and to be strongly impacted by climate change, with wide-ranging consequences for human societies and ecosystems (IPCC 2014). Rising global temperature is expected to enhance the intensification of the hydrological cycle, resulting in more severe dry seasons and wetter rainy seasons, and subsequently heightened risks of more extreme weather and frequent floods and drought. Changing climate will also have significant impacts on the availability and accessibility of water, both qualitatively and quantitatively. It is predicted that between 75 and 250 million people will be exposed to increased water stress due to climate change by the year 2020 (IPCC 2007).

Melting glaciers has led to rise in sea levels which are currently aggravating flood frequencies in several parts of West Africa. In drier regions, a slight rise in temperature leads to greater loss of moisture, exacerbating drought and desertification. Drought leads to decreased water availability and water quality for populations in many water-scarce regions, particularly in the semi arid regions of West Africa. When less precipitation and higher temperatures occur simultaneously, the availability of water resources is reduced even further because of increased evaporation, leading to a vicious cycle. This has led to the occurrence of long periods of drought which are predicted to become more widespread in future (IPCC 2007).

Climate change has also been found to have direct influence on watershed degradation in West Africa. Watershed degradation is often expressed in form of sedimentation of water courses, reservoirs and coasts, increased runoff and flash flooding, reduced infiltration to groundwater, water quality deterioration, and depletion of soil productivity. Lebel (2003) reported a severe decrease of river flows in the Niger basin as a result of the droughts of the 1960s. The reduction in the area of Lake Chad discussed above was revealed by several authors to be due to similar reasons (Olivry et al. 1996). Pruski and Nearing (2002) indicated that erosion increased by 1.7% for every 1% increase in total rainfall and rainfall intensity. Legesse et al. (2003) predicted a decrease of runoff by 30% in response to a 10% decrease in rainfall amount while considerable increase of 1.5% in air temperature would result in a smaller runoff decrease of only 15%. Mkankam Kamga (2001) revealed that in the Sahelian region of Cameroon, an increase of temperature of 1 and $3^0$C and changes in rainfall amount of +4% and -13% would result in variations in annual river fluxes of respectively -3% and +18%. The perturbation of downstream hydrology by the transformation of hydrological transport characteristics as a result of changes in rainfall intensity was revealed by Hodgkins et al. (2003).

The aforementioned perturbation of hydrological balance and water resources generally is expected to aggravate the challenges of food insecurity by reducing the production capacity of the rain-fed agricultural production systems of West Africa. Agriculture provides a source of employment for more than 60 percent of the population and rain-fed agriculture constitutes over 90 percent of the total cropland (Benedict et al. 2014). This over reliance on climate has exposed the agricultural systems to extreme inter and intra seasonal variability in rainfall. Consequently, yield from West African agriculture has been predicted to fall by 50 percent in 2020 (IPCC 2007). Significant warming has also been predicted which will affect crop marginal water balance and further harm the agricultural sector (Mendelsohn et al. 2000). These problems will be exacerbated by poor information, slow technological change, and heavy dependence of domestic economies on the weak agro-based economic systems.

The Niger River Basin has been identified as one of the river basins most affected by climate change. Precipitation is highly variable spatially and temporally in the basin (Lekan and Shakirudeen, 2010). Extreme events of precipitation also increase the frequencies of flood and drought in the basin. In the past 50 years, reduction in rainfall of 10 to 30% in the basin has led to a deficit of 20 to 60% in river discharge (Novotny and Stefan 2007). The River dried up for several weeks at Malanville in the Benin Republic in 1985 as a result of a one-year lag of lowest rainfall and runoff in 1984 (Legesse et al. 2003). These have great implications for downstream hydrological systems such as the Kainji Lake, Nigeria. Salami and Sule (2010) identified long term significant fluctuations in reservoir balance and the hydraulic heads in the lake as a result of climate variability. The continual expansion of the lake reservoir as a result of extreme hydrological events was also reported by Ikusemoran (2009). David and Salami (2012) attributed the sudden lake expansion and contractions in the Kainji lake to discharges at the reservoirs located in the Upstream (Niger Republic and Mali). These challenges - if unabated - might aggravate the food and energy crisis in Nigeria, the most populous country in Africa. Thus, there is an urgent need to comprehend the impacts of climatic changes in the basin in order to ensure sustainable integrated watershed management. Consequently, this study evaluated how hydro-climatic changes in the Niger basin influences hydrological properties and functioning of the Kainji Lake, Nigeria.

### *1.1 Justification*

The Niger River Basin, home to approximately 100 million people, is a vital, complex asset for West Africa. River Niger is the continent's third longest river, flowing through nine countries; Benin, Burkina Faso, Cameroon, Chad, Côte d'Ivoire, Guinea, Mali, Niger, and Nigeria. The Niger River embodies the livelihoods and geopolitics of the nations it crosses. This river is not simply a body of water, but is also an origin of identity, a route for migration and commerce, a source of potential conflict, and a catalyst for cooperation (KfW 2010).

While the upper and middle Niger has seen little regulation through artificial lakes/dams, the lower Niger is endowed with the Kainji lake which is the main source of water for agriculture and hydroelectric power in the region. Multiple influences of climate change and human activities (waste disposal, urban runoff, effluent discharges from industries and decrease of forest areas) have greatly impacted the hydrologic dynamics of the Niger. This has caused significant fluctuations in river discharge which has great implications for the downstream Kainji lake in the lower Niger. This study was intended to give good insight into the multiple causes of these fluctuations and its implications for the hydrology and functioning of the Kainji lake which is one of the most economically important man-made lakes on the Niger. In view of this, this study assessed the extent to which climatic changes influenced the Niger basin and their effects on hydrological properties and functioning of the Kainji lake in Northern Nigeria.

### *1.2 General Objective*

The aim of this study was to increase our understanding of how and to what extent climatic changes in the Niger basin could affect hydrological systems. The study evaluated the effects of climatic changes in the Niger Basin on the hydrological properties and functions of the Kainji Lake, Northern Nigeria.

### *1.3 Specific Objectives*

Four specific objectives are designed to aid in the effective achievement of the main goal:

(1) Evaluation of climate trends and populations' perceptions in the Niger basin;
(2) Assessments of trends of projected 21$^{st}$ century climate change in the Niger basin;
(3) Hydrological modeling of projected climate change impacts on water resources in the Niger Basin;
(4) Assessments of impacts of future climate change on hydropower production in the Niger basin;

### 1.4 Thesis Structure

This thesis is organized in eight chapters. Chapter 1 gives a general introduction that reviews existing literature on the subject, states the problem and justifies the present study. Climate change assessments, modeling framework and brief information on the Niger basin is in Chapter 2. Chapter 3 gives the findings on the trends and local perceptions of historic climate change from the middle to the lower Niger basin. Chapter 4 focuses on the assessments of trends of projected 21st century climate change in the Niger basin. Chapter 5 is on hydrological modeling of projected climate change impacts on water resources in the Niger basin. Chapter 6 describes the impacts of future climate change on hydropower production in the Niger basin. Chapter 7 gives general discussion, conclusions and recommendations. Bibliographies and references are highlighted in Chapter 8.

# CHAPTER 2

## Literature Review

### 2.1 Concepts and definitions

This section provides definitions of frequently used terms concerning climate change based on IPCC (2014). The definition facilitates information exchange among climate researchers, and also improves the understanding of climate change research by broad readership.

*Climate change:* Climate change refers to a change in the state of the climate that can be identified (e.g., by using statistical tests) by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer. Climate change may be due to natural internal processes or external forcings such as modulations of the solar cycles, volcanic eruptions, and persistent anthropogenic changes in the composition of the atmosphere or in land use. Note that the Framework Convention on Climate Change (UNFCCC), in its Article 1, defines climate change as: "a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods." The UNFCCC thus makes a distinction between climate change attributable to human activities altering the atmospheric composition, and climate variability attributable to natural causes.

*Hazard:* The potential occurrence of a natural or human-induced physical event or trend or physical impact that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems, and environmental resources. In this report, the term hazard usually refers to climate-related physical events or trends or their physical impacts.

*Exposure:* The presence of people, livelihoods, species or ecosystems, environmental functions, services, and resources, infrastructure, or economic, social, or cultural assets in places and settings that could be adversely affected.

*Vulnerability:* The propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt.

## 2.2 Overview of Impacts of Climate Change on Water Resources

This section was described with the United Nations Environment Programme (UNEP) handbook on climate change (1998). The section takes a comprehensive view of climate change impacts on water resources such as water demand and water resources management as well as water supply. Water resources management (i.e., the water supply infrastructure and operating procedures) is an important aspect of climate change assessment because it is used to redistribute water supply both spatially and temporally to meet water demand. Insights can be gained and conclusions drawn from analyzing only the physical impacts on water supply and water demand, but the focus of the approach presented here is to provide the potential impact of climate change on water resources which are summarized below.

### *2.2.1 Biophysical Impacts*

Hydrologic resources: The main components of the hydrologic cycle are precipitation, evaporation, and transpiration. Changes in the climate parameters – solar radiation, wind, temperature, humidity, and cloudiness – will affect evaporation and transpiration. Changes in evapotranspiration and precipitation will affect the amount and the distribution, spatially and temporally, of surface runoff. Changes in runoff in combination with sea level rise will affect streamflow and groundwater flow. Streamflow and groundwater are considered natural water or hydrologic resources.

Water quality**:** All off stream water withdrawals change the chemical, biological, or thermal quality of the water during use, and when that water is released back to the stream, it can affect the water quality of the receiving water body. For water quality and environmental protection needs, the water management system can be designed to provide either dilution flows or wastewater treatment. Climate change can affect the water quality aspect of the water management system in three ways. First, reduced hydrologic resources may leave less dilution flow in the stream, leading to degraded water quality or increased investments in wastewater treatment. Second, higher temperatures reduce the dissolved oxygen content in water bodies. Third, in response to climate change, water uses, especially those for agriculture, may increase the concentration of pollution being released to the streams. Together, these pose a threat to the water quality and the integrity of the aquatic ecosystem.

Aquatic ecosystem: There are many complex interactions among the elements of the aquatic ecosystem. Climate is a direct input to the energy source and chemical variables of the system, and an indirect input to the flow regime, habitat structure, and biotic factors. These elements are in a sensitive balance. Even a slight change to just a few of the key elements can greatly affect the integrity of the ecosystem.

### *2.2.2 Socio-economic impacts*

Water demand: Water use is generally divided into non-market and market uses. Nonmarket water uses are aesthetic uses, certain recreational uses, and aquatic ecosystem integrity. Market water uses can be aggregated into five major water use sectors:

- Agriculture: Irrigation and livestock;

- Industry: Industrial, mining, navigation, recreation;
- Energy: Thermoelectric cooling and hydroelectric power;
- Municipal: Public supply, domestic, and commercial;
- Reservoir.

An additional market use is water dilution for pollution abatement. It is typically considered a market use because it can be valued at the cost savings of additional waste treatment to meet water quality standards.

Water management system: The water management system (i.e., water supply system) is made of two parts: surface water and groundwater. Although they are linked at the river basin water balance level, they are distinct in the water supply infrastructure. Climate change can affect surface water supply via reduced flows into the storage reservoir or increased variability in inflow, which will affect firm yields from existing storage facilities. An additional impact in arid and semi-arid regions could be increased reservoir evaporative losses. The groundwater supply will be affected by increased or decreased percolation of water due to changes in the amount and distribution of precipitation and streamflow. This can lead to increased pumping costs if percolation decreases because of decreased precipitation or losses of soil moisture from increased evapotranspiration.

### 2.3 Climate Change Impact Assessment for Water Resources

Climate change impact assessment refers to research and investigations designed to find out what effects future changes in climate could have on human activities and the natural world. Climate change impact assessment is also frequently coupled with the identification and assessment of possible adaptive responses to a changing climate. To the extent that adaptation can reduce impacts, the assessment of adaptation measures is part of impact studies. Thus impacts may be described as “gross” or unmodified impacts and as “net” impacts after adaptation has been taken into account. Climate change impact studies are necessarily conjectural. That is to say, impacts cannot usually be experimentally confirmed or verified. Clearly it is not possible to conduct a controlled experiment by changing the global atmosphere to test the effects of changes on human and natural systems.

With great uncertainties about the local and regional impacts of climate change on hydrologic resources and uncertain future water demands driven by socio-economic change, an assessment of climate change impacts on water resources is a complex process. In addressing the sensitivity of water resources to changes in climate, the biophysical and socio-economic conditions must be considered.

This section gives insight into the steps and range of methods that are appropriate for estimating:

(1) biophysical impacts of climate change on hydrologic resources in terms of water quantity (annual and seasonal distribution) and quality, and aquatic ecosystem effects; and

(2) socio-economic impacts of climate change on both water demand (including direct impacts on hydrologic resources and indirect impacts via other biophysical impacts) and water resources management parameters (including, but not limited to, river runoff, reservoir yields, supply reliability, hydropower production, water use, supply/demand balances, effects and costs of adaptation, and economic impacts with and without adaptations).

## 2.4 Methods and Tools Selection

There is a range of different approaches or methods that can be used in the assessment of climate change impacts. These include quantitative and predictive models, empirical studies, expert judgments, and experimentation. Each of these approaches has its own advantages and weaknesses, and a good strategy may be to use a combination of approaches in different parts of the assessment or at different stages of the analysis. In addition to formal modeling approaches, consideration should also be given to methods of stakeholder involvement, and the use of expert judgments. In some cases, empirical studies of current climate impacts may be useful. There are also other tools that may be used, such as geographic information systems (GIS) and remote sensing. Each of these is briefly described below. Consideration should be given to using these approaches in appropriate combinations.

### *2.4.1 Quantitative models*

Where feasible, it is desirable to use models where the variables can be expressed in quantitative terms, so that a variety of tests can be carried out (e.g. sensitivity tests), and so that results can be expressed in more precise terms. However, one has to keep in mind that the results generated by these models may look very precise, but should be handled with caution since the underlying assumptions – not only climate and socioeconomic scenarios but also assumptions about processes – can be rather weak or incorrect.

There are broadly three kinds of quantitative models that can be used in climate impacts studies:

- ✓ biophysical models,
- ✓ socio-economic models, and
- ✓ integrated system models.

The ideal that is being sought is a model or models which deal with climate and socioeconomic and natural systems in an interactive way. Many of the available models, however, are simple cause and effect models, in which one or more climatic variables are changed and the consequences predicted and measured. In reality, we have an interactive system in which one set of cause and effect relationships leads to another. The integrated systems models represent an on-going effort to deal with this complexity.

### *2.4.2 Empirical studies*

Empirical observations of the interactions of climate and society and natural systems can be of value in anticipating future impacts. This is commonly achieved through analogue methods, in which variations over space or past time can substitute for future changes. Three kinds of analogue can be identified: historical events, historical trends, and regional or spatial analogues of present climate. A particular advantage of empirical studies emerges as they are extended into the area of adaptation because it becomes possible to ask decision makers, stakeholders, and those impacted directly about how they adapt or have adapted in the past. It is also possible to confirm their responses through direct observations.

Empirical studies can be combined effectively with quantitative model scenarios. Such a combination of approaches permits modeling work to be solidly grounded in experience, and permits the extension of empirical studies into the future.

### *2.4.3 Expert and stakeholder judgment and participation*

A useful method of obtaining a rapid assessment of the state of knowledge concerning the likely impacts of climate change is to solicit the judgments and considered opinions of experts in this and related fields. The use of expert judgment may be especially appropriate in preliminary or pilot studies, as discussed above. Expert judgment may therefore be used in anticipation of other types of approach, and be an aid in the design of such studies. The use of expert judgment can also be formalized into a quantitative assessment method, by classifying and then aggregating the responses of different experts to a range of questions.

## 2.5 Types of Climate Change Scenarios

There are three generic types of climate change scenarios: scenarios based on outputs from GCMs, synthetic scenarios, and analogue scenarios. All three types have been used in climate change impacts research. This section briefly describes each type:

### *2.5.1 General circulation models*

GCMs are mathematical representations of atmosphere, ocean, ice cap, and land surface processes based on physical laws and physically-based empirical relationships. Such models have been used to examine the impact of increased greenhouse gas concentrations on future climate. GCMs estimate changes for dozens of meteorological variables for grid boxes that are typically 250 kilometers in width and 600 kilometers in length. Their resolution is therefore quite coarse. The most advanced GCMs couple atmosphere and ocean models and are referred to as coupled ocean- atmosphere GCMs.

Two types of GCM runs can be useful for impact assessments. GCMs are used to run equilibrium experiments where both the current and future climates are assumed by modelers to be in equilibrium (i.e., stationary). The second type of experiment that GCM is used for is called a transient experiment. Here, a coupled GCM is used to simulate current ($1HCO_2$) climate and then future climate as it responds to a steady increase in greenhouse gas concentrations beyond $1HCO_2$ concentrations (Mitchell et al. 1995).

A major disadvantage of using GCMs is that, although they accurately represent global climate, their simulations of current regional climate are often inaccurate. In many regions, GCMs may significantly underestimate or overestimate current temperatures and precipitation. Another disadvantage of GCMs is that they do not produce output on a geographic and temporal scale fine enough for many impact assessments. GCMs estimate uniform climate changes in grid boxes several hundred kilometers across, and although they estimate climate on a daily or even twice daily basis, results are generally archived and reported only as monthly averages or monthly time series. An additional disadvantage of GCM-based scenarios is that a single GCM, or even several GCMs, may not represent the full range of potential climate changes in a region.

Although GCMs have clear limitations for scenario construction, they do provide the best information on how global and regional climate may change as a result of increasing atmospheric concentrations of greenhouse gases.

### *2.5.2 Synthetic scenarios*

Synthetic scenarios, sometimes referred to as arbitrary scenarios, are based on incremental changes in such meteorological variables as temperature and precipitation. For example, temperature changes of +2°C and +4°C can be combined with precipitation changes of 10 percent or 20 percent or no change in precipitation to create a synthetic scenario. These incremental changes are usually combined with a baseline daily climate database to yield an altered 30-year record of daily climate.

The main advantages of synthetic scenarios are their ease of use and transparency to policy makers and other readers of impacts studies. In addition, synthetic scenarios can capture a wide range of potential climate changes. One can examine small changes in climate (e.g. 1°C) up to large changes in climate (e.g. 5°C to 6°C), and one can examine increased and decreased precipitation scenarios. In addition, because individual variables can be changed independently of each other, synthetic scenarios also help identify the relative sensitivities of sectors to changes in specific meteorological variables. A further advantage of synthetic scenarios is that different studies can use the same synthetic scenarios to compare sensitivities.

Synthetic scenarios are inexpensive, are quick and easy to construct, and generally require few computing resources.

A major disadvantage of synthetic scenarios is that they may not be physically plausible, particularly if uniform changes are applied over a very large area or if assumed changes in variables are not physically consistent with each other. Synthetic scenarios may not be consistent with estimates of changes in average global climate. This last limitation can be overcome by using the outputs of GCMs to guide the development of synthetic scenarios.

### *2.5.3 Analogue scenarios*

Analogue scenarios involve the use of past warm climates as a scenario of future climate (temporal analogue scenario), or the use of current climate in another (usually warmer) location as a scenario of future climate in the study area (spatial analogue scenario).

Since temporal analogues of global warming were not caused by anthropogenic emissions of greenhouse gases and because spatial analogues are unlikely to be plausible climate, experts have generally recommended that these types of scenarios should not be used (Carter et al. 1994).

### *2.5.4 Combinations of options*

None of the above options fully satisfies all scenario selection conditions. Sulzman et al. (1995) therefore recommend using a combination of scenarios based on outputs from GCMs and synthetic scenarios. They advocate using GCM-based scenarios because they are the only ones explicitly based on changes in greenhouse gas concentrations. Synthetic scenarios complement GCM scenarios because they allow for a wider range of potential climate change at the regional level and are easier to construct and apply.

## 2.6 Methods of Enhancing the Spatial Variability of Climate Change Scenario

There are a number of options for manipulating the spatial variability of a climate change scenario. Some scenarios contain only a uniform change in climate over an area. Because of the lack of precision about regional climates in a GCM, Von Storch et al. (1993) advocated that, in general, the minimum effective spatial resolution should be defined by at least four GCM grid boxes. The skill of GCM simulations for an individual grid box will depend, however, on the spatial autocorrelation of the particular weather variable. However, the detailed descriptions of two methods are presented below:

### *2.6.1 Downscaling*

The two main approaches to downscaling use either regression relationships between large area and site-specific climates (e.g Wigley et al. 1990) or relationships between atmospheric circulation types and local weather (e.g Von Storch et al. 1993). When applied to daily GCM data, these techniques offer the prospect of generating daily climate change scenarios for specific sites or catchments. The disadvantage of downscaling approaches is that they require large amounts of observed data to calibrate the statistical relationships and can be computationally very intensive. Such methods are also time consuming since unique relationships need to be derived for each site or region. Downscaling methods are also based on the fundamental assumption that the observed statistical relationships will continue to be valid in the future under conditions of climate change.

### *2.6.2 Regional models*

Downscaling techniques are statistical methods for generating greater spatial variability in a climate change scenario. An alternative approach involves the use of high resolution regional climate models (RCMs; also called limited area models, LAMs). Regional climate models are typically constructed at a much finer resolution than GCMs (often 50 kilometres), but their domain is limited to continents or subcontinents. Although RCMs yield greater spatial detail about climate, they are still constrained at their boundaries by the coarse-scale output from GCMs. To an extent, therefore, the performance of an RCM can only be as good as that of the driving GCM. The costs of establishing a regional climate model for a new region and running a climate change experiment are extremely high, both computationally and in terms of human resources.

## 2.7 Climate change uncertainty

One of the major challenges both for climate modelers and users of climate change information is how to deal with uncertainty. Sources of uncertainty, which are not exclusive to climate change, are numerous, such as lack of information or knowledge, natural variability and processes that are essentially unpredictable. In climate change, rather than adopting a best or worst case scenario or an average of scenarios, it is commonly preferred to use a set of alternative scenarios and also from different GCMs. This helps to explore a whole range of plausible scenarios, thus addressing the uncertainty of climate change and its impacts in a more effective way. Accurate predictions will never be achieved given the complexity of the earth-ocean-atmosphere processes coupled to greenhouse gas emissions, land surface modifications and some feedback mechanisms which cannot be adequately modeled.

## 2.8 Study Area

### *2.8.1 The Niger Basin and Climate Change*

The Niger River Basin is generally considered to be one of the river basins most affected by freshwater shortages. Precipitation is very variable spatially and temporally in the basin. Precipitation amounts from one year to another shows wide variations, as it is within the year. Apart from the variability of the annual and seasonal rainfalls, extremes of precipitation result in floods and droughts at different times and sometimes within the same period. This section briefly describes some significant impacts of climate change in the Niger basin following the description of the Olomoda (2006) and KfW (2010).

### *2.8.2 General description of the Niger River basin*

The Niger River Basin covers 2.27 million $km^2$, with the active drainage area comprising less than 50% of the total (KfW 2010).With a length of 4,200 km, the river is the third longest in Africa after the Nile and the Congo River. It traverses four countries, two of which (Niger and Nigeria) are named after it. The basin is shared among 10 countries: Nigeria (27%), Mali (26%), Niger (24%), Algeria (8%), and Benin, Burkina Faso, Cameroon, Chad, Cote d'Ivoire and Guinea (each <5%) (KfW 2010). However, the active drainage area is less than half of the basin and excludes Algeria. The Niger crosses areas with different climatic characteristics. A large part of the river basin is located in the Sahel, a semiarid area between the Sahara desert and the Sudan savannas. Due to the topographical and hydrological characteristics, the river is often divided into four sub basins: the Upper Niger Basin, the Central Delta, the Middle Niger Basin and the Lower Niger Basin.

The source of the Niger is located close to the *Fouta Djallon* Mountains in the South of Guinea at an altitude of approximately 800 m. With more than 2,000 mm per year, the area receives a high amount of rainfall. The river flows northeast through the Upper Niger Basin. Several tributaries provide additional water, until the Niger enters the Inner Delta in Mali. During the rainy season, the delta forms a large flood plain of 20,000 to 30,000 km², facilitating the cultivation of rice, cotton and wheat as well as cattle herding and fishing. The size of the flooded area is subject to strong annual variations, depending on the discharge of the Upper basin. A large part of the water is lost in the delta due to evaporation and seepage. According to the FAO, almost two thirds of the water is lost in the Inner Delta. After the Inner Delta, the Niger reaches the fringes of the Sahara desert and turns southwards, passing Niamey, the capital of Niger. Further downstream, the Niger River enters Nigeria and receives water from large tributaries. It flows into the Atlantic Ocean at the Gulf of Guinea. The river facilitates hydropower generation, irrigated agriculture, fishing and navigation and is a crucial factor for the economy in West Africa. Hence, variations in the river flow have an immense impact on the people who depend on it.

## 2.9 Historical Trends of Climate Change and Variability

### *2.9.1 Rainfall*

The seasonal pattern and amount of rainfall in all areas depend on the latitude and position of the Intertropical Convergence Zone (ITCZ), which migrates between north and south during the year. Compared to the period from 1951 to 1969, isohyetal lines shifted about 150 to 250 km southward in the period from 1970 to 1988. Similarly, Olomoda (2006) found that the 200 mm isohyetal line shifted 100 km southward when comparing the average of the years 1950-1967 to the period 1968-1995. When analyzing the rainfall data of the 20th century, a remarkable break becomes visible in 1970, with a wet period before and a dry period after that year. Since the 1990s however, rainfall has slightly increased at least in the Central Sahel.

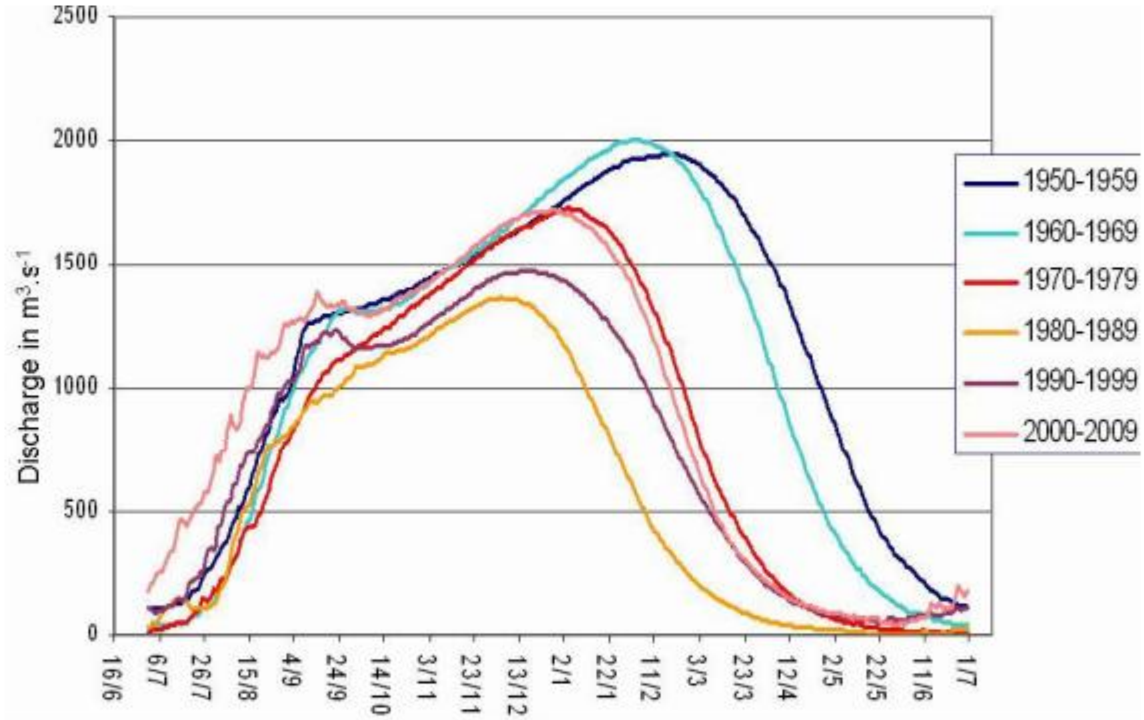



**Fig 2. 1 Average hydrographs of the Niger River by decades at the Niamey station.**

Source: Amogu et al.( 2010)

### *2.9.2 Discharge*

Since the past 5 decades, the Niger basin has been affected by series of climatic changes causing extreme low flows along the river. For example in June 1985, the river Niger was completely dry in Niamey. This phenomenon was almost repeated in June 2002 when the flow recorded fell among the lowest in 50 years. The Niger basin's theoretical area of about 2 million sq km has also been reduced to an active catchment area of just about 1,500,000 sq km thereby excluding Algeria. Amogu et al.( 2010) identified three groups of decadal discharge evolutions on the Niger basin (Fig 2.1): the first group includes the 1950s and the 1960s, well known as a humid period. The second group is composed of the 1980s and 1990s and constitutes the dry periods. The third group is made up of the 1970s and the 2000s and represents the decreasing (1970s) and increasing (2000s) stages of the long-term drought.

# CHAPTER 3

## Hydro-Climatic Changes in the Niger Basin and Consistency of Local Perceptions

This chapter is based on:

Oyerinde, G.T., Hountondji, F.C.C., Wisser, D., Diekkrüger, B., Lawin, A.E., Odofin, A.J., Afouda, A., 2014. Hydro-climatic changes in the Niger basin and consistency of local perceptions. Reg. Environ. Chang. 15, 1627–1637. doi:10.1007/s10113-014-0716-7

### 3.1 Introduction

Climate change has significant impacts on ecosystems and societies in West Africa and adaptation to it is hindered by poorly documented historical climate trends and future projections. Historical climate trends are not properly captured in the region due to inadequate and deteriorating amount of reliable observation stations since 1980 (Ali and Lebel 2009). Satellite-based observations of precipitation have also been identified with inherent biases in the region as a result of insufficient ground-based data for calibration and validation (Sylla et al. 2013). This has led to contradictory results from climate trend studies at local and sub regional scales. For instance, following the 1990's report of the Sahelian drought (Le Barbé and

Lebel 1997; Sivakumar 1992), several studies considered it either ended in the 1990's (Ozer et al. 2003), continued (Dai et al. 2004; Hulme 2001; L'Hote et al. 2002) or even was simply an artifact of changing station networks (Chappell and Agnew 2008). The recent discovery of a precipitation gradient from eastern to western Sahel (Lebel and Ali 2009) in addition to the north-south Inter Tropical Convergence Zone (ITCZ) influence on rainfall distribution is also a factor of importance for reliable hydrological predictions in West Africa.

For future conditions, no coherent projection for either decreasing or increasing precipitation emerges from global climate model (GCM) products (Druyan 2011). This lack of consensus among GCM projections was attributed to the unclear West African monsoon precipitation response to anthropogenic climate change (Biasutti and Giannini 2006; Douville et al. 2006; Giannini et al. 2008). In addition, the typical grid box of GCMs (in the range of 100–400 km) is too coarse to account for land surface heterogeneities from vegetation, topography, and coastlines, which are important for the physical response governing the local and regional climate change signal (Paeth et al. 2006; Rummukainen 2010). Regional Climate Models (RCM) can potentially overcome this limitation; however, Diallo et al.(2012) found mixed results in terms of RCMs improving the simulation of climate patterns compared to the driving GCMs.

These climate uncertainties exacerbate the vulnerability of West African populations both to high natural variability of climate and anticipated climatic changes in the future (Mertz et al. 2011). High population density, large growth rates and the dependence on rainfed agriculture make economies particularly vulnerable. The prominent West African average rainfall deficit of 180 mm in 1970s and 1980s relative to the 1950s and 1960s (Le Barbé et al. 2002) resulted in severe famine and crop failure (Ben Mohamed et al. 2002). The increase of precipitation since 1990 (Lebel and Ali 2009) aggravated the intensities of floods in the region; Yabi and Afouda (2012) reported the disruption of agricultural activities during extreme rainfall years in Benin which swept out over 24% of the state revenue from agriculture. Increases in West Africa's air temperature could further increase the vulnerability of agriculture through a yield reduction as a result of heat stress, although large discrepancies exist in yield predictions as a result of climate change in West Africa and the sign of change is uncertain (Roudier et al. 2011).

The Niger River Basin, the largest basin in the region was also identified with uncertainties and contradictory hydro-climatic information. A vivid example is the 'Sahelian paradox' which is an observed runoff increase in some of the basin's Sahelian catchments such as in Nakanbe (Burkina Faso), Sirba (Niger) and Mekrou (Benin) despite a decrease in rainfall (Descroix et al. 2009; Mahe et al. 2005). This was attributed to soil crusting and land degradation as a result of unsustainable land use in the basin (Amogu et al. 2010). High rainfall spatial and temporal variability in the basin has significant impacts on water resources (Oyebande and Odunuga 2010). In the past 50 years, a 10 to 30% decrease in mean annual rainfall in the basin has led to a reduction of 20 to 60% in river discharge (Oyebande and Odunuga 2010). Even with no change in precipitation, the availability of per capita renewable water resources in the basin is declining as a result of a large population growth; the population in the basin is expected to double from 94 million in 2005 to over 150 million by the year 2050, and competing demands have led to challenges in water allocation among different users and countries (Ogilvie et al. 2010). A sustainable management strategy is therefore needed to cope with challenges arising from increases in water demand and changes in the variability of supply in the basin.

Local communities in the Niger basin have responded to variations in water availability through the use of water harvesting, irrigation, planting of drought tolerant and early maturing crop varieties, and others. Therefore, knowledge of local communities on recent climate variability (< 20 years) and adaptation measures is very valuable, particularly in the absence of reliable local observations and projections. Several studies such as (Fosu-Mensah et al. 2012; Kemausuor et al. 2011; Mertz et al. 2009; Tambo and Abdoulaye 2012; West et al. 2008) have already displayed high consistencies between local perceptions and observations. The IPCC Summary for Policymakers (2014) also showcased that “adaptation planning and implementation at all levels of governance are contingent on societal values, objectives, and risk perceptions”. However, some biases are witnessed in local perceptions, which are caused by some environmental factors such as extreme droughts. Such bias was witnessed in Ethiopia where the perceived 1980s' dry years due to large-scale famine conditions were one of the wettest years in the region (Meze-Hausken 2004). Kalanda-Joshua et al. (2011) also reported that local perceptions is based on the ability of respondents to recall key events and are thus more accurate on recent climatic events (< 30 years). This study aimed at ameliorating these challenges by evaluating consistency of local perceptions with recent observations starting from 1990; after recovery from the West African drought was witnessed in some parts of the region (Ali and Lebel 2009). We also assessed the potential of local perceptions in enhancing adaptation efforts in the Niger River Basin.”

The objectives of the study were to:

- evaluate trends of precipitation, river discharge and local perceptions in Malanville (Benin) and Kainji (Nigeria) settlements along the Niger river,

- assess the agreement of local perceptions with hydro-climatic observations, and
- evaluate local adaptation mechanisms to climate change.

## 3.2 Data and Methods

## 3.3 Study Area

The Niger River Basin covers 2.27 million $km^2$ (Ogilvie et al. 2010) and with 4200 km in length the Niger is the third longest river in Africa. The basin consists of ten countries including some parts of Benin and Nigeria, where the study sites (Malanville and Kainji) are located (Fig 3.1). Malanville commune (lowest administrative level in Benin) covers an area of 3016 $km^2$ and had a population of about 160000 people in 2013 (INSAE 2013). It has a mean annual precipitation of about 800 mm (based on observations from 1950 to 2010) which is concentrated in one rainy season from mid April to mid October. During the dry season, Malanville is subject to the Sahelian northeast trade wind that comes with relatively cool and dry environmental conditions. Highest temperatures of about 46 °C are recorded in March and April while the lowest temperatures (about 16 °C) are observed in December and January, with an annual average of 28 °C based on the same observation period.

Downstream of Malanville is the Kainji lake which resulted from a multipurpose dam project installed in 1968 (Fig 3.1). The purposes of the reservoir include power generation, progressive development of navigation, flood control in the Niger valley, and estimated fishery production of over 10000 tons annually. The reservoir has a total storage volume of 15 $km^3$ and a surface area of 1270 $km^2$ at maximum water surface elevation (Jimoh 2008). Kainji dam has eight hydropower plants with a total installed capacity of 760 MW (Jimoh 2008) and supplies 12 per cent of the total electricity of Nigeria (Mohammed et al. 2013). Since 1990, more frequent extreme events in inflow to the reservoir have led to increased downstream spill discharge, sometimes resulting in floods downstream. Such aggravated flooding

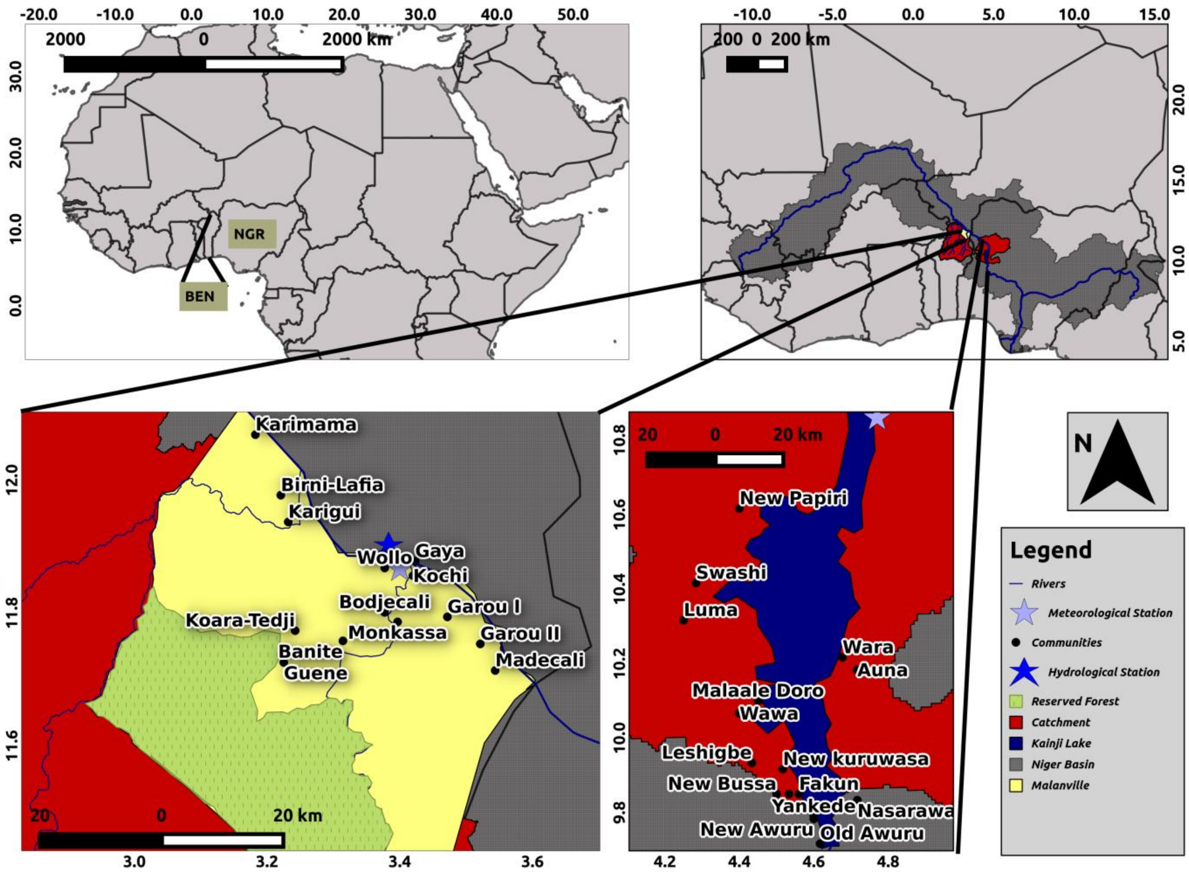



**Fig 3. 1 Location of sampled communities in Malanville (Benin) and Kainji (Nigeria)**

was witnessed in some downstream communities in 1997 and 1998 when properties worth over 3 million USD were destroyed (Salami and Sule 2010).

## 3.4 Data Collection

### *3.4.1 Hydro-climatic data*

To analyze shifts in the regimes of hydro-climatic variables in the study areas, we collected historical records of precipitation and river discharge. At Malanville, daily precipitation was available for the period 1950 to 2010 and daily river discharge from 1952 to 2010. At Kainji, we evaluated daily precipitation from 1972 to 2010. Daily hydrological records (reservoir level and outflow) of Kainji Lake were obtained from Kainji Hydro-Electric Power Authority for a ten year period (the maximum length of records that was made available) from 2001-2010.

### *3.4.2 Socioeconomic data*

A survey with a questionnaire addressing climate trends and adaptation mechanisms (Table 3.1) was used to investigate the perception of climate variability/change and adaptation of the local population to those changes. From September to November, 2012, a total of 239 questionnaires were administered through a personal oral interview. The respondents were from thirty different communities (3.1), fourteen along the Niger and its tributaries (Sota, Alibori and Mekrou) in the Malanville area and sixteen in the Kainji Lake area.

## Table 3. 1 Variables of the socioeconomic survey conducted in Malanville (Benin) and Kainji (Nigeria)

| **Group of Variables** | **Variables** | **Description** |
|---|---|---|
| **Hydro-climatic variability** | ***Rainfall*** | Observed trend of precipitation |
| | ***Dynamics of water bodies*** | Observed trend of river discharge |
| | ***Climate change*** | Awareness about climate change and its impacts |
| **Extreme events** | ***Flood*** | Observed trend of flood occurrence |
| | ***Rainfall Frequency*** | Frequency of rainfall |
| **Adaptation Mechanism** | ***Soil and water conservation mechanism*** | Local land conservation techniques |
| | ***Flood adaptation*** | Management strategies for ameliorating impacts of floods |
| | ***Declining rainfall adaptation*** | Strategies of resilience to decline in rainfall |

A total of 120 and 119 respondents were respectively interviewed in both areas. The respondents were randomly selected from the communities, with the community sample weighted with population size. The majority of respondents in Malanville are involved in multiple farming practices; 61% are involved in crop farming, 21% are into livestock production, 11% are involved in fish farming and the remaining 7% are engaged in other activities. At Kainji, 27% of respondents are located downstream of the Kainji dam while 73% were upstream of the dam.

In line with the methodology of Tambo and Abdoulaye (2012), respondents were initially asked whether they had heard or read about climate change in order to ascertain their level of awareness. This was followed by questions regarding their perceptions of changes in rainfall and river discharge in the area over the past 20 years, their perceived impacts of climate change on water resources and adaptation mechanisms (Table 3.1). Data obtained from the questionnaires were analyzed and compared with the respective hydro-climatic observations.

### 3.5 Data Analysis

To detect significant shifts in hydroclimatology (the annual total rainfall, number of rainy days - a rainy day was defined as a day when total rainfall was > 0.1 mm - and average discharge at Malanville), we used the regime shift detection definition of Rodionov & Overland (2005);

A regime shift occurs when a statistically significant difference exists between the mean value of the variable before and after a certain point in time based on the t-test. For each observation $x$ in a time series, a test is performed to determine whether it represents a statistically significant deviation from the mean value of the current regime ($x_{mean}^{curr}$). According to the t-test, the difference (*diff*) between $x_{mean}^{curr}$ and mean value of the new regime ($x_{mean}^{new}$) will be statistically significant at the level p if it satisfies the condition:

$$diff = |x_{mean}^{new} - x_{mean}^{curr}| = t\sqrt{2s_t^2/l} \qquad \textbf{EQ 1}$$

where $t$ is the value of $t$-distribution with $2l – 2$ degrees of freedom and $l$ is the number of years. In this study, three probability levels $p$ (0.01, 0.05 and 0.10) were tested to assess the magnitude of the shifts. It was assumed here that variances for both regimes were the same and equal to the average variance for running $l$-year intervals in the time series ($x_i$). We also analyzed intra decadal variations of the Kainji reservoir release and water level for 3 year intervals between 2002 and 2010.

## 3.6 Results

## 3.7 Climate Trends and Local Perceptions

A regime shift towards a decrease in total annual rainfall ($p = 0.05$) was observed at Malanville from 1959 until 2008 when a significant increase ($p = 0.05$) was observed (Fig 3.2a). The same pattern of a significant rainfall increase ($p = 0.01$) in 2008 was prominent in Kainji (Fig 3.2b). The claim of increasing rainfall by 97% of respondents in Malanville was in line with these observations (Fig 3.2a). At Kainji, on the other hand, 63% of upstream and 78% of downstream respondents believed they witnessed less rainfall compared to past decades (Fig 3.2b).

Lower rainfall frequency was reported in Malanville which was in line with observed trend of the decreasing number of rainy days (Fig 3.2c). An upward shift in number of rainy days ($p = 0.1$) was observed at Malanville between 1965 and 2000 when there was a downward shift in regime of rainy days (Fig 3.2c). Higher rainfall frequency was reported by 59% and 72% of the downstream and upstream respondents in Kainji which was also in line with recent observed trend of increasing number of rainy days (Fig 3.2d). A downward shift in number of rainy days ($p = 0.1$) was observed between 1982 and 2007, a period after which an upward shift is observed (Fig 3.2d).

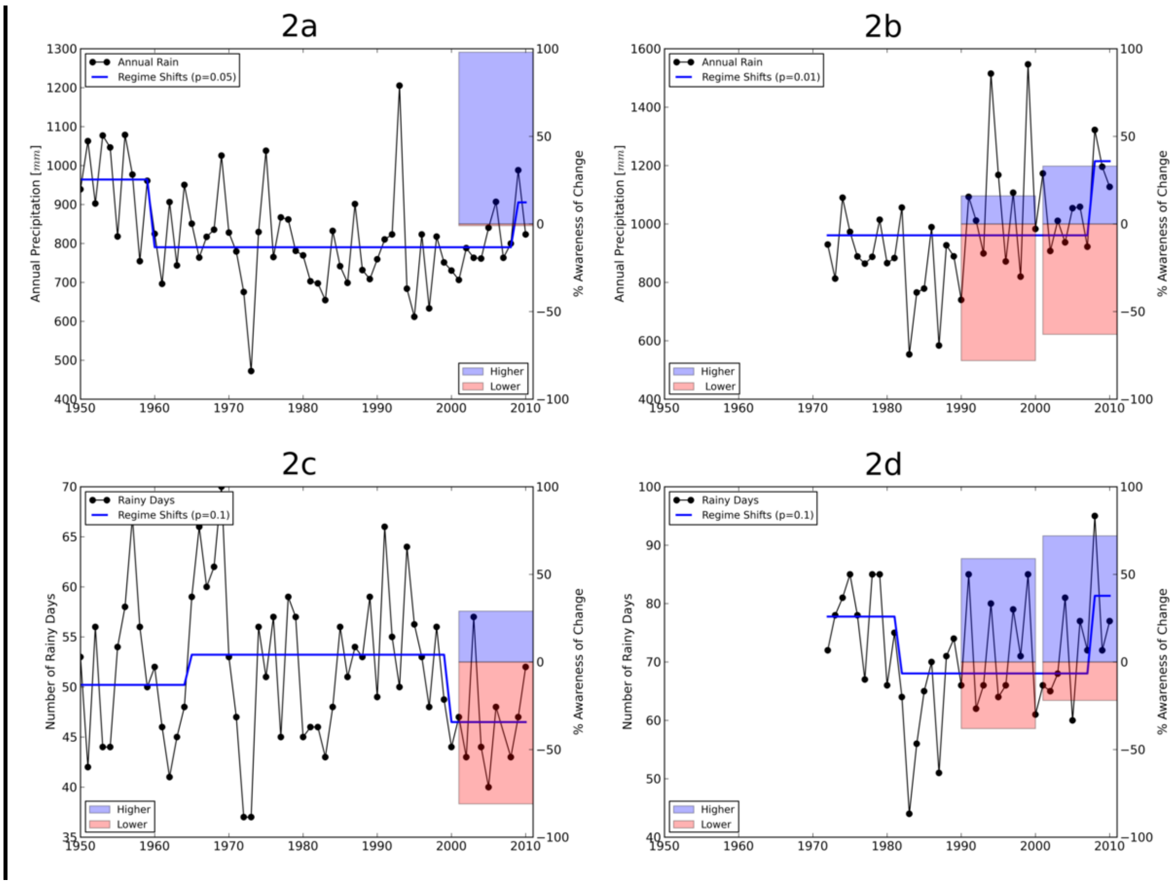



**Fig 3. 2 Observed and local perceptions of rainfall trends and number of rainy days;**

*(2a) Annual Rainfall at Malanville (2b) Annual Rainfall at Kainji (2c) Number of Rainy Days at Malanville (2d) Number of Rainy Days at Kainji; Boxes (Kainji, left = downstream and right = upstream) show percentage of respondents stating higher (blue) or lower (red) conditions.*

In Malanville, 87% of the respondents were aware of climate change and its impacts on water resources (Table 3.2); 78% reported it led to increase in river discharge, 82% highlighted greater floods, and 63% revealed that there was more water stress compared to the past. At Kainji, perception of climate change were dependent on location relative to Kainji dam, 97% and 88% downstream and upstream respondents disclosed that they were aware of climate change and its influence in the region (Table 3.2). Ninety-four and eighty-six percent of the respondents from downstream and upstream said climate change led to high river flow/discharge; flood and water stress was dominant downstream Kainji dam as disclosed by 91% and 69% respectively.

A vast majority (90%) of the respondents in Malanville disclosed that higher river flow led to greater floods in the area (Fig 3.3). Observations revealed that the Niger river discharge at Malanville experienced a downward shift ($p = 0.1$) in 1971 and 1985; however, increasing discharge ($p = 0.1$) was observed from 1994 until 2010 (Fig 3.3). At Kainji, greater flooding was dominant downstream of the dam as disclosed by 84% of the respondents; against 19% upstream respondents (Fig 3.4). Dynamics of the reservoir level of Kainji dam (Fig 3.4) showed slight fluctuations in upstream water level in the three evaluated time slices. Downstream outflow from the lake showed a rapid increase from August to November in 2008-2010 which was not observed in other evaluated periods.

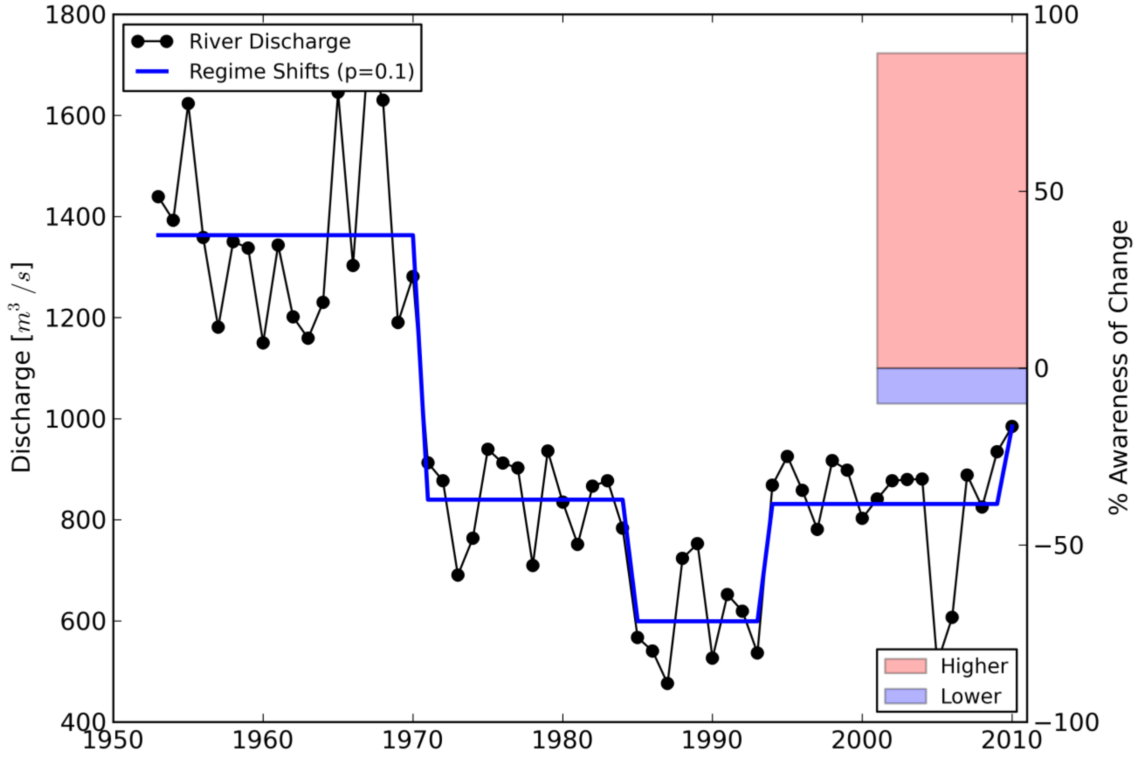



**Fig 3. 3 River discharge trend and flood perception in Malanville;**

*Boxes show percentage of respondents stating higher (red) or lower (blue) conditions*

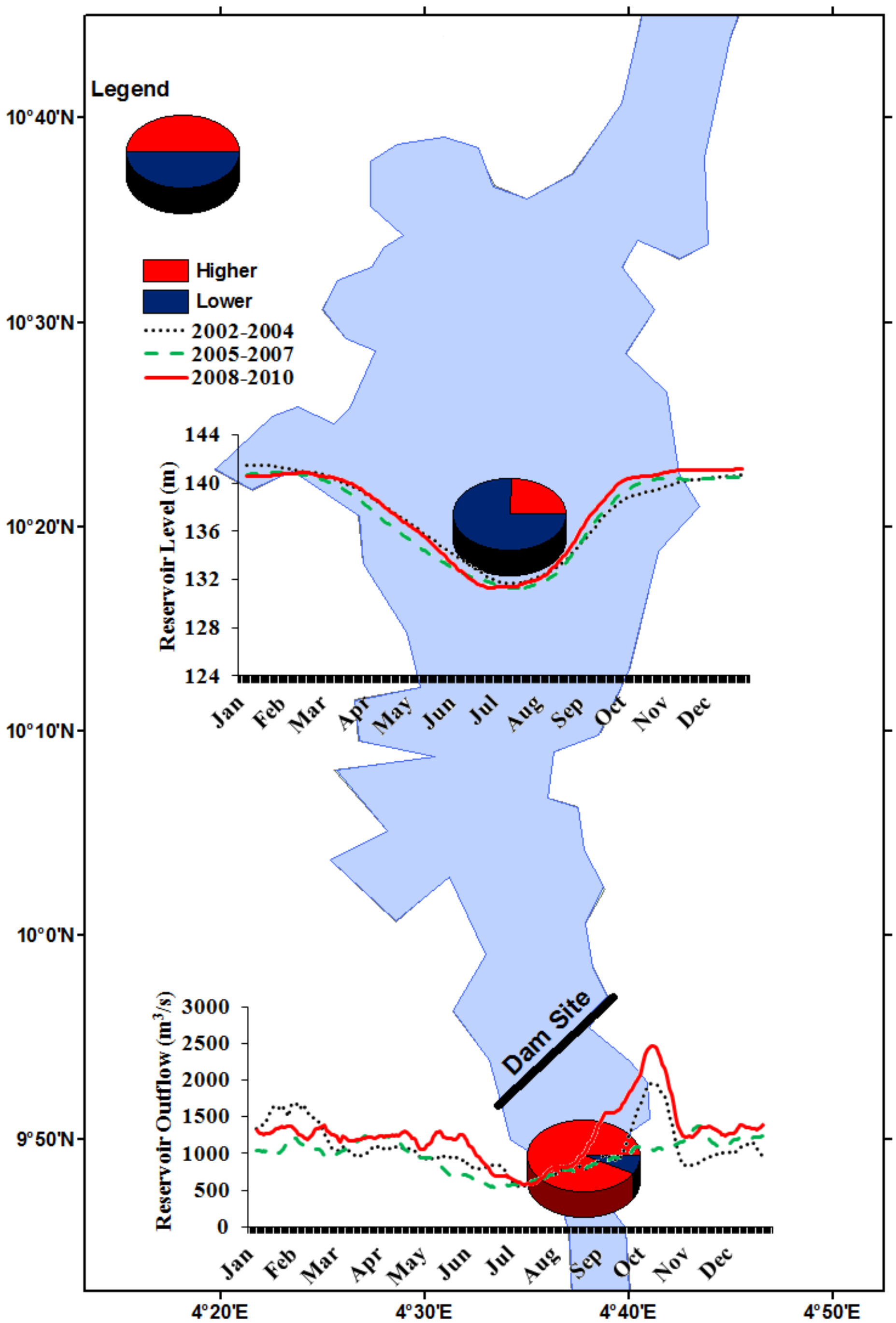



**Fig 3. 4 River discharge trend and flood perception in Kainji;**

*pies show percentage of respondents stating higher (red) or lower (blue) conditions while lines are 11 days moving averages of the time slices*

At Malanvile, 98% of the respondents disclosed rainfall as a key climate variable that affected their activities, 81% agreed on land (soil and water) availability as another main factor which determined their production (Table 3.2). The importance of alternative water supply for agriculture (irrigation/animal watering) and domestic purposes was revealed by 59% (Table 3.2). In Kainji, above 98% on both sides of the dam revealed rainfall as a key climate variable that affected their activities while 63% downstream and 48% upstream identified land (soil and water) availability as another main factor which determined the extent of their production. Eighty-one percent of downstream and twenty-nine percent of upstream respondents disclosed the availability of alternative water supply as a variable factor of economic production.

**Table 3. 2 Perceptions of climate and socio-economic change in Malanville and Kainji.**

| Variable Groups | Variables | Malanville (%) | Kainji (%) | |
|---|---|---|---|---|
| | | | Downstream | Upstream |
| **Climate Change Awareness** | ***Yes*** | 87 | 97 | 88 |
| | ***No*** | 13 | 3 | 12 |
| **Effects of Climate Change on Water Resources** | ***+Flow*** | 78 | 94 | 86 |
| | ***+Flood*** | 82 | 91 | 43 |
| | ***+Water Stress*** | 63 | 69 | 51 |
| **Determinant of Economic Activities** | ***Rainfall*** | 98 | 100 | 98 |
| | ***Land*** | 81 | 63 | 48 |
| | ***Alternative Water Sources*** | 59 | 81 | 29 |

### 3.8 Adaptation mechanisms

Adaptation methods employed in the two locations are indicated in Table 3.3 and Fig 3.5. Although most of the respondents claimed that they had perceived at least one change in climatic attributes, 52% of Malanville, 38% of upstream (Kainji) and 75% downstream (Kainji) respondents had adaptive measures (Table 3.3). Investigation of adopted soil and water conservation mechanisms in Malanville (Fig 3.5a) indicated that above 86% respondents deployed local drinking water treatment such as water sediment coagulation, 44% engage in measures of flood control, 58% in agroforestry (mixed cultivation of crops and economic trees), 52% in measures of reclamation of flooded areas (land reclamation), and 48% adopted soil amendments with fertilizers.

At Kanji, there were differences in adaptation measures depending on the location (upstream or downstream) of the dam (Fig 3.5a). Seventy-five percent of respondents downstream embraced flood control as valid means of adaptation while only 18% of respondents' upstream used flood control. Fifty and twenty-six percent of respondents downstream and upstream used water storage, 75% and 43% respondents downstream and upstream deployed treatment of water, respectively. Agroforestry was practiced by 50% downstream and 78% upstream, soil amendments were generally low (28% downstream and 32% upstream) and land reclamation was not a common practice in the area.

## Table 3. 3 Adaptations to Climate Change in Malanville and Kainji

| Variable | Response | Malanville (%) | Kainji (%) | |
|---|---|---|---|---|
| | | | Downstream | Upstream |
| Deployment of Adaptation Methods | Yes | 52 | 75 | 38 |
| | No | 48 | 25 | 62 |
| Early Warning Systems | Yes | 43 | 47 | 53 |
| | No | 57 | 53 | 47 |
| NGOs | Yes | 31 | 0 | 7 |
| | No | 49 | 81 | 84 |
| | I don’t Know | 20 | 19 | 9 |
| Recovery Aid | Yes | 39 | 6 | 7 |
| | No | 61 | 94 | 93 |
| Collaboration | Yes | 25 | 9 | 10 |
| | No | 42 | 28 | 72 |
| | I don’t Know | 33 | 63 | 17 |

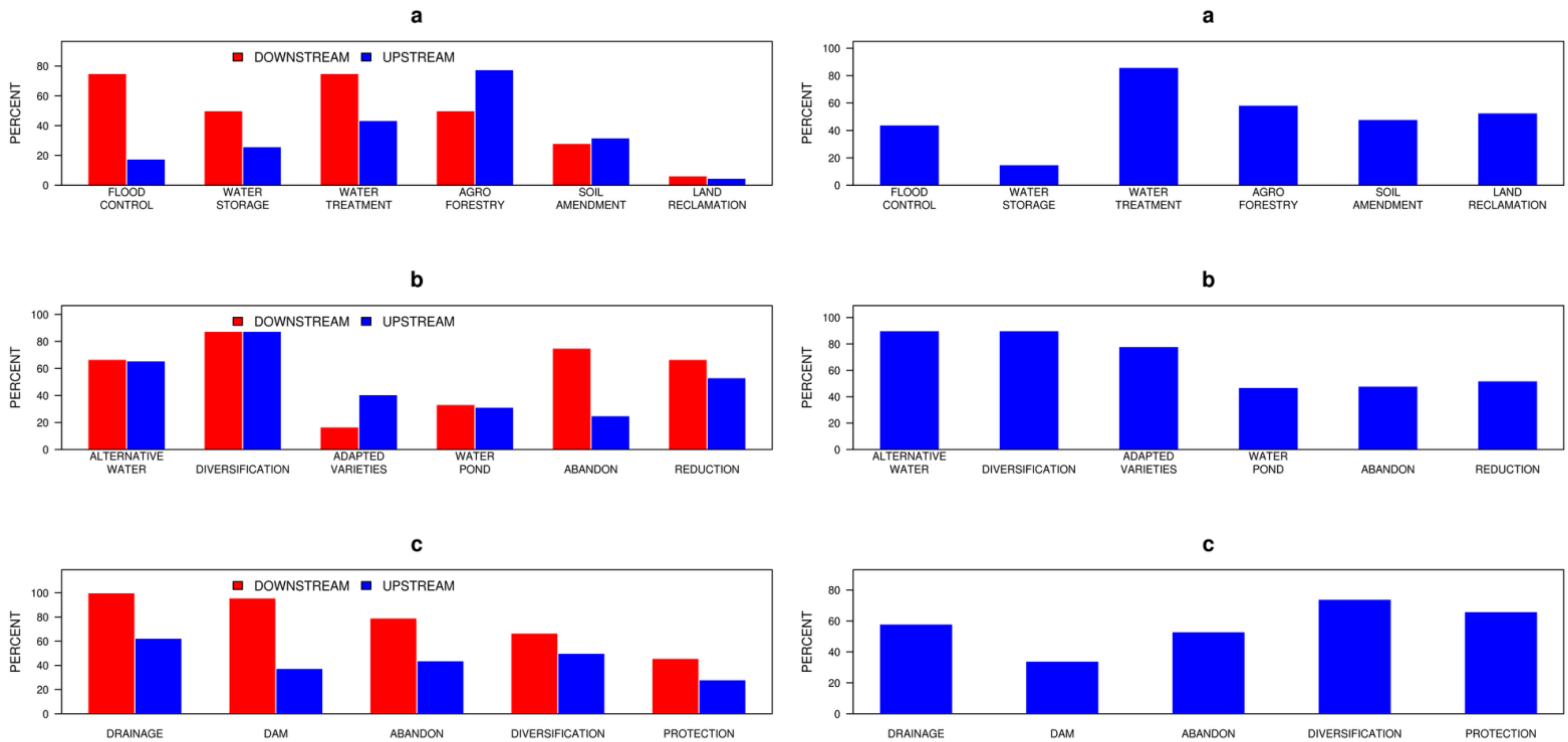



**Fig 3. 5 Adaptation mechanisms in Kainji (left) and Malanville(right)**

*(a) General soil and water conservation mechanisms (b) Declining rainfall adaptations (c) Flood adaptations*

Malanville residents responded to declining rainfall by seeking alternative water supply (for domestic use, irrigation and animal watering) from rivers, lakes and small wells (Fig 3.5b). They also used adapted crop varieties or moved into other economic activities (diversification). Other methods are the reduction of the cultivated area, or the use of small ponds. Some farmers (48%) abandoned their production. The residents of Kainji responded to decline in rainfall by seeking alternative water sources, diversification into non agricultural activities (such as selling water to other households) and reduction of the farm size (Fig 3.5b). The use of adapted varieties and small water ponds was not embraced in Kainji and abandoning of farmlands was reported downstream by 75% of the respondents. In order to adapt to extreme flood events in Malanville, more than 70% of respondents diversify into other sources of income for the duration of the flood (Fig 3.5c). Other deployed methods are the construction of dam/dikes, drainage, abandoning of flooded farm lands and protection of exploited areas (such as reinforcement of open water ponds by fish farmers) (Fig 3.5c). At Kainji, more than 90% of the respondents downstream used drainage and small dam/dikes for flood protection while only 63% and 38% of upstream respondents used such methods (Fig 3.5c). Other embraced flood adaptation mechanisms in Kainji included abandoning of production land and diversification into other sources of income. Protections of properties during floods were not prominent in the area.

The level of institutional adaptations investigated in Malanville revealed that access to early warning systems of extreme events is low in the area (43%). Access to governmental recovery aid was experienced by 39% of respondents while activities of non-governmental organizations (NGOs) such as raising the awareness on impacts of climate change and capacity building on methods of resilience against floods were witnessed by 31% of the respondents (Table 3.3). Inter-communal collaborations in combating impacts of floods on the communities were also reported to be low (Table 3.3). Activities of NGOs in Kainji were also low as highlighted by none of downstream and 7% of upstream respondents. Governmental recovery aid was given to 6% and 7% downstream and upstream respondents while early warning systems were available to 47% and 53% respondents at the downstream and upstream respectively (Table 3.3). Inter-communal collaborations were also low in Kainji (Table 3.3).

## 3.9 Discussion

The observed significant decrease ($p = 0.05$) in rainfall at Malanville since 1970 was the result of a 150 km downward shift in rainfall isohyets which resulted into rainfall deficit of 180–200 mm all over West Africa from 1970-1990 compared to 1951-1969 (Lebel and Ali 2009). The observed increase in rainfall from 1990-2010 in Malanville ($p = 0.05$) and Kainji ($p = 0.01$) was due to regional increasing rainfall pattern in the eastern part of the Sahel (Amogu et al. 2010). This phenomenon was accrued with higher rainfall in July compared to

1970-1989 dry periods (Lebel and Ali 2009). The observed significant increase in discharge since 2007/2008 in Kainji and Malanville ($p = 0.1$) has increased the flooding risk and in combination with increasing population pressure led to greater economic implications of flooding in the two study sites. This is in line with the observations of Sarr (2012) who reported an increase in annual flood events in 2007, 2008 and 2009 compared to annual floods from 1966 to 1980 in West Africa. Water levels in Kainji Lake showed less variability as a result of the reservoir operation to maintain a high water level for hydropower production. However, during high inflow, excess water is discharged through the spill gates and can result in severe flooding downstream.

There was a close agreement between local perceptions and observed trends in the two locations especially in the most recent years. Higher rainfall was declared by respondents from Malanville which was in line with analysis of regime shifts. Decreasing and increasing number of rainy days prominent in Malanville and Kainji was in line with local perceptions of lower and higher frequency of rainfall in the two sites. The strong consistency between the observations and the local perceptions was also observed by Kalanda-Joshua et al. (2011) in Malawi where local perceptions adequately capture recent key climatic events. Mertz et al.(2009) made similar observations in Eastern Saloum (Senegal) where farmers were strongly aware of climate and had clear opinions on changes. Similar matching between local perceptions and observed trends was reported in Ghana by Kemausuor et al.(2011). These studies also emphasized that local perceptions of climatic changes can be used to complement climatic studies and reduce effects of uncertain regional observations. Based on studies in Benin, Cuni-Sanchez et al.(2012) suggested the use of local perceptions for complementing climatic studies in the absence of reliable records. Local observations could be used in determining data transferability to poorly gauged basins. They can also give a pointer to overlooked aspects and thus assist in formulating viable research questions (Byg and Salick 2009a) along with assistance in co-ordination of intervention efforts.

However, the discrepancies between perceptions upstream and downstream of the dam highlighted some important sources of bias in local perceptions when compared with climate observations. Higher percentage of respondents upstream the Kainji dam perceived the recently increasing rainfall trend ($p = 0.01$) since 2008 (Fig 3.2) against their downstream counterparts. Rainfall station located at the upstream, tip of the Kainji lake (Fig 3.1), might not effectively capture rainfall trends in far away communities. Similar observations were made in Ethiopia by Meze-hausken (2004) where available monthly rainfall records hide changes in seasonal rainfall patterns and led to some deviation between observations and local perceptions. Morestill, the operation of the dam separates the effects of river flow and has lead to different adaptation measures upstream and downstream. For this is relevant for designing adequate interventions for individual communities around Kainji rather than treating the area as a single unit. This is in line with the observations of Byg and Salick (2009), who reported that perceptions gives fine scale information which are shaped by local geographical region, climatic differences and subsistence activities. Reported higher water stress across the communities despite an increase in rainfall and discharge may be due to effects of population pressure and confirm previous findings that population growth will place severe constraints on water availability for development in Africa (Falkenmark 1990). A well-engineered efficient water use system might be advantageous in mitigating water-related constraints on development in the region (Vörösmarty and Douglas 2005).

Despite the enormous climate change challenges in the study area and the impacts of flood and drought on the economic activities of the local population, only about 50% of the respondents deployed adaptation measures (Table 3.3). This can be generally attributed to inadequate and poorly coordinated governmental and non-governmental interventions. Involvement of local populations in designing and implementing these interventions could reduce effects of hydro-climatic changes and improve adaptive capacity of the region (Sissoko et al. 2010). Higher adaptation of residents downstream Kainji dam was due to flooding witnessed as a result of spill discharge from the reservoir and shows that people that experiences frequent flooding express more concern and greater willingness to take action against climate change (Spence et al.

2011). Respondents embraced the use of local level water treatment as a result of inadequate drinking water supplies which keep the communities on high alert of water borne disease like cholera that is rampant in the region (Okeke et al. 2001). Other methods of climate change adaptations include flood control which was disclosed to be highly important for Malanville and residents downstream of the Kainji dam.

### 3.10 Conclusions

Our study highlights the importance of indigenous knowledge in climate change assessments and adaptations. We evaluated the consistency of local knowledge and responses to climate change with observations of hydro-climatic variables in two Niger basin settlements. The two settlements (Malanville and Kainji) along the Niger river have gone through significant variations in precipitation and river discharge which has different impacts at the local scale. Perceptions of climate indicators were highly consistent with observations demonstrating the value of local knowledge. Indigenous people that carry large share of climate change effects are typically excluded from official climate interventions (Green and Raygorodetsky 2010) but the integration of their knowledge could reduce effects of deteriorating hydro-climatic observations and enhance sustainable adaptations. Local populations gave important information that could improve our understanding of climate trends in data scarce regions. However, impacts of these climatic changes were dependent on environmental factors (such as the location relative to a dam) and how this is captured in local perceptions depends on people's memory capability in recalling recent events. These need to be taken into account when evaluating and using local people’s knowledge. Further research should aim at unveiling methods that could be used to maximize exploration of local intelligence on climate change and to help develop locally targeted sustainable adaptation measures.

# CHAPTER 4

## Projected 21$^{st}$ Century Climate Change in The Niger Basin

### 4.1 Introduction

Climate-change impacts are expected to exacerbate poverty in most developing countries and create new poverty pockets in countries with increasing inequality, in both developed and developing countries (IPCC 2014). West Africa's hydrological systems are facing significant changes due to global warming and climate change. This is evident with the recent droughts and floods which have great impacts on the hydrological balance of the region. Water column stratification increases in the regional lakes (IPCC 2014), reduction in the area of lake Chad have also been prominent since 1970s (Olivry et al. 1996). Climate change have led to reduced discharge in West African rivers and increased soil moisture drought in the Sahel since 1970; although partially wetter conditions was experienced since 1990 (IPCC 2014).

The Niger River Basin - home to 100 million people - is a vital asset for West Africa, a developing region, which is unfortunately subject to challenges of climate change. In the past 50 years, reduction in rainfall of 10 to 30% in the basin has led to a deficit of 20 to 60% in river discharge (Novotny and Stefan 2007). Lebel (2003) reported a severe decrease of the river flows in the Niger basin as a result of the droughts of the 1960s.  The river dried up for several weeks in 1985 at the Malanville (Republic of Benin) point, as a result of a one-year lag of lowest rainfall and runoff in 1984 (Legesse et al. 2003). An analysis of selected locations in the upper and middle Niger basin showed that projections by GCMs and 20 AR4-models were not consistent regarding rainfall and runoff changes, making management of hydrological projects in the Niger basin difficult (KfW 2010).

Several studies such as Sylla et al. (2010); Mariotti et al. (2011); Diallo et al. (2012); Oguntunde and Abiodun (2013); Laprise et al. (2013); Ibrahim et al. (2013) and Panitz et al. (2013) evaluated future patterns of climate change in the region. However, most of these studies used a single RCM and GCM projection. Multi-model ensembles of models, both of GCMs and RCMs, have been suggested to be a better predictor than individual climate models (Lambert and Boer 2001). In line with the study of Diallo et al. (2012), this study presents ensembles of future climate predictions from 8 different GCMs in order to obtain a better understanding of future climate trends in the Niger basin, thereby aiding policymakers for mitigation and adaptation planning.

## 4.2 Materials and Methods

### *4.2.1 Study Area*

The Niger River Basin covers 2.27 million km$^2$ (Ogilvie et al. 2010), at 4200 km in length, the basin being the third longest in Africa (Fig 4.1). It is shared by ten countries (Algeria, Benin, Burkina Faso, Cameroon, Chad, Cote d'Ivoire, Guinea, Mali, Niger and Nigeria) with its source located close to the Fouta Djallon Mountains in the south of Guinea at an altitude about 800 m (Oguntunde and Abiodun 2013). The Niger crosses areas with different climatic characteristics. A large part of the river basin is located in the Sahel, a semiarid area between the Sahara desert and the Sudan savannas. Precipitation ranges from 250 to 750 mm/year in the Sahelian/desert zone to over 2,000 mm/year close to the river mouth in the Guinean/coastal zone with length of rainy season varying from 3 to 7 months (KfW 2010). River discharge ranges from $500m^3/s$ at the head waters to above $5000m^3/s$ at the basin outlet (Fig 4.1). The river flows northeast through the Upper Niger basin and enters the Inner Delta in Mali. It then flows southeastern through Niger, Benin and Nigeria, where it connects the Atlantic Ocean at the Gulf of Guinea. Its main tributary, the Benue River, flows from highlands of Cameroon and joins the Niger in Nigeria, before reaching the Atlantic Ocean.

### *4.2.2 Data*

We used rainfall data from a set of 8 CMIP5 GCMs (Table 4.1) with two emission scenarios. The GCMs were downscaled to 0.44° x 0.44° (approximately 50km) resolution with the SMHI-RCA (Sveriges Meteorologiskaoch Hydrologiska institute) RCM within the CORDEX-Africa regional downscaling experiments. The Coordinated Regional Downscaling Experiment (CORDEX) is a program sponsored by World Climate Research Program (WCRP) to develop an improved framework for generating regional-scale climate projections for impact assessment and adaptation studies worldwide within the IPCC AR5 timeline and beyond. Climate projection framework within CORDEX is based on the set of new global model simulations planned in support of the IPCC Fifth Assessment Report (referred to as CMIP5). This set of simulations includes a large number of experiments, ranging from new greenhouse-gas scenario simulations for the 21st century, decadal prediction experiments, experiments including the carbon cycle and experiments aimed at investigating individual feedback mechanisms (Taylor et al. 2012). These simulations are based on the reference concentration pathways (RCPs), i.e. prescribed greenhouse-gas concentration pathways throughout the 21st century, corresponding to different radiative forcing stabilization levels by the year 2100. Within CMIP5, the highest-priority global model simulations have been selected to be the RCP4.5 and RCP8.5, roughly corresponding to the IPCC SRES emission scenarios B1 and A1B, respectively (Giorgi et al. 2009). The same scenarios are therefore also the highest priority CORDEX simulations (Giorgi et al. 2009). Catchment boundary of the Niger basin was obtained from Hydrosheds.

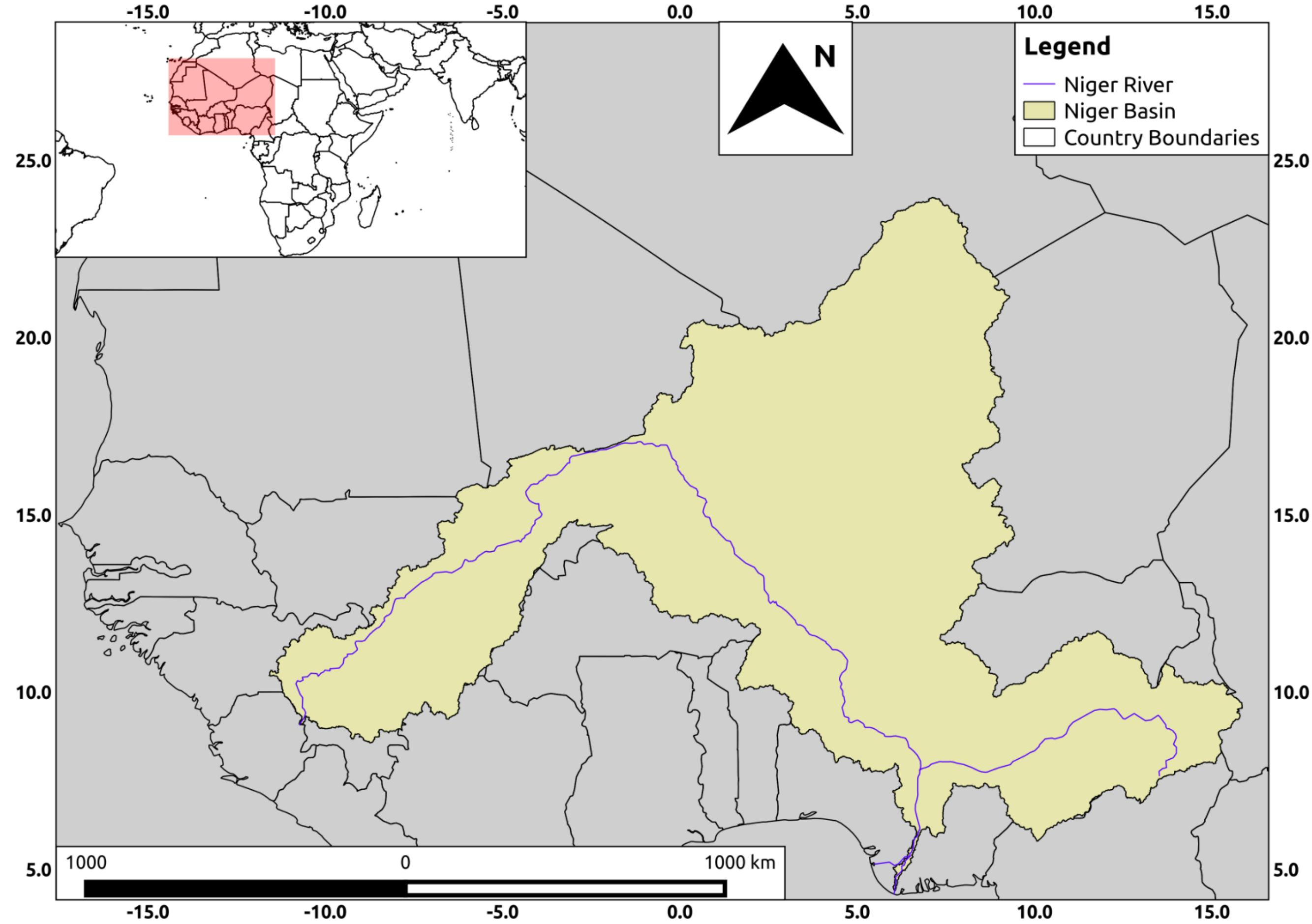



**Fig 4. 1 The Niger Basin.**

## Table 4. 1 List of CMIP5 models considered in the study

| Modeling Center (or Group) | Institute ID | Model Name | Resolution |
|---|---|---|---|
| Canadian Centre for Climate Modelling and Analysis | CCCMA | CanESM2 | T63 (;2.8125832.81258) L35 |
| Centre National de Recherches Météorologiques / Centre Européen de Recherche et Formation Avancée en Calcul Scientifique | CNRM-CERFACS | CNRM-CM5 | TL127 (256 3 128) |
| NOAA Geophysical Fluid Dynamics Laboratory | NOAA GFDL | GFDL-ESM2M | M45 (;2832.58) L24 |
| Met Office Hadley Centre (additional HadGEM2-ES realizations contributed by Instituto Nacional de Pesquisas Espaciais) | MOHC | HadGEM2-ES | N96 (;1.24831.8758) L38 |
| Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology | MIROC | MIROC5 | T85 (;1.40625831.406258) L40 |
| Max-Planck-Institut für Meteorologie (Max Planck Institute for Meteorology) | MPI-M | MPI-ESM-LR | T63 (;1.875831.8758) L47 |
| Norwegian Climate Centre | NCC | NorESM1-M | F19 (;1.875832.58) L26 |
| EC-EARTH consortium | EC-EARTH | EC-EARTH | TL159 (320 3 160) |

Rainfall and temperature distribution in West Africa have been attributed with the back and forth movement of the Inter Tropical Convergence Zone (ITCZ) (Lucio et al. 2012). The movement of the ITCZ follows the position of maximum surface heating associated with meridional displacement of the overhead position of the sun, lower latitudes experience higher rainfall and lower temperature, whereas higher latitudes experience lower rainfall and higher temperatures. This creates a large rainfall gradient across latitudes which need to be considered in the study. Basin satellite rainfall and temperature series were calculated as the weighted average of all grid boxes by latitudes. For extraction of rainfall, higher latitudes were given lower weights than the lower latitudes while the reverse was applied for temperature.

We computed catchment potential evapotranspiration (PET) from extracted temperature with the Hamon model (Oudin et al. 2005) . The model was selected based on a recent finding that very simple evapotranspiration models relying on mean daily temperature are as efficient as more complex models such as the Penman model and its variants (Oudin et al. 2005).

Evaluation of CORDEX Africa climate models was done by Kim et al. (2013) who reported that CORDEX Africa RCMs reasonably simulated basic climatological features of some climate variables. Mounkaila et al. (2014) showed that CORDEX RCMs have remarkable skills in predicting the rainfall-onset dates in West Africa. Laprise et al. (2013) also disclosed that CORDEX Africa regional model is able to add value compared to the simulations of the driving GCMs. Based on these findings, this study evaluates 21st century projected climate trends in the Niger basin with data obtained from CORDEX Africa RCM SMHI-RCA (Sveriges Meteorologiskaoch Hydrologiska institute) forced by 8 GCMs under the mild (RCP4.5) and high (RCP8.5) emission scenarios.

### *4.2.3 Spatio-temporal climate trends*

Ensembles of models, both of GCMs and RCMs, were reported as better predictor than individual models (Lambert and Boer 2001). Spatial pattern of ensemble median of changes of eight GCMs relative to the present-day reference period of 1970–1999 were evaluated in two future 30 years periods: the Near term (2030–2059) and Far term (2070-2099). Annual and seasonal climate trends from 2010 to 2100 relative to 1970-1999 were presented in line graphs.

Trends were calculated as:

$$\left(\frac{x_{fut}^{i} - \overline{x_{hist}}}{\overline{x_{hist}}}\right) X\ 100$$

$x_{fut}^{i}$ is the regional future (2010-2100) climate variable x of year i and $\overline{x_{hist}}$ is the historical (1970-1999) regional average of climate variable x.

To determine the wet or dry character of the 21st century. Annual Standardized Precipitation Index (SPI) was calculated as defined by Ali and Lebel (2009) and aggregated to 30 years climatological regimes from 1950 to 2100.

$$\frac{P_R^i - \overline{P_R}}{\sigma_R}$$

Where $P_R^i$is the rainfall of year i, $\overline{P_R}$ is the interannual rainfall average and $\sigma_R$ is the standard deviation of $\overline{P_R}$.

## 4.3 Results

Figure 4. 2 shows spatial trends of projected precipitation in far and near terms for two scenarios (RCP4.5 and RCP8.5) over the Niger basin. Projected 21st century annual and seasonal rainfall trends in the Niger basin are showcased in figures 4.3 and 4.4, SPI annual and seasonal trends are prescented in figures 4.5 and 4.6, annual and seasonal rainfall trends of temperature and PET are prescented in figures 4.7 to 4.9 .

### *4.3.1 Rainfall*

Figure 4.2 compared the Niger basin's spatial distribution of projected rainfall trends (relative to 1970-1999) in the Near and Far term under RCP4.5 and

RCP8.5 emission scenarios. RCP4.5 ensemble median projections in the Niger basin showcased in Figure 4.2 revealed above 5% increase at the source and in the Sahelian parts of the basin. The Guinea regions around Nigeria are expected to experience about 5% decrease towards the end of the century. Under RCP8.5 scenario the basin will experience above 20% increase in the most parts of the basin as we move toward the end of the 21st century.

Annual and seasonal ensemble median projected climate patterns on the Niger from 8 GCMs are displayed in Figures 4.3 and 4.4. In the RCP4.5 scenario (Fig 4.3), there will be about 2% increase in annual rainfall from middle to the end of the century while in the higher emission scenario (Fig 4.3), the basin will go through an increasing trend with about 5% at the middle of the century to about 10% with low confidence level at the end of the century. From Fig 4.4, DJF precipitation projections were attributed with low model agreements in the two scenarios.

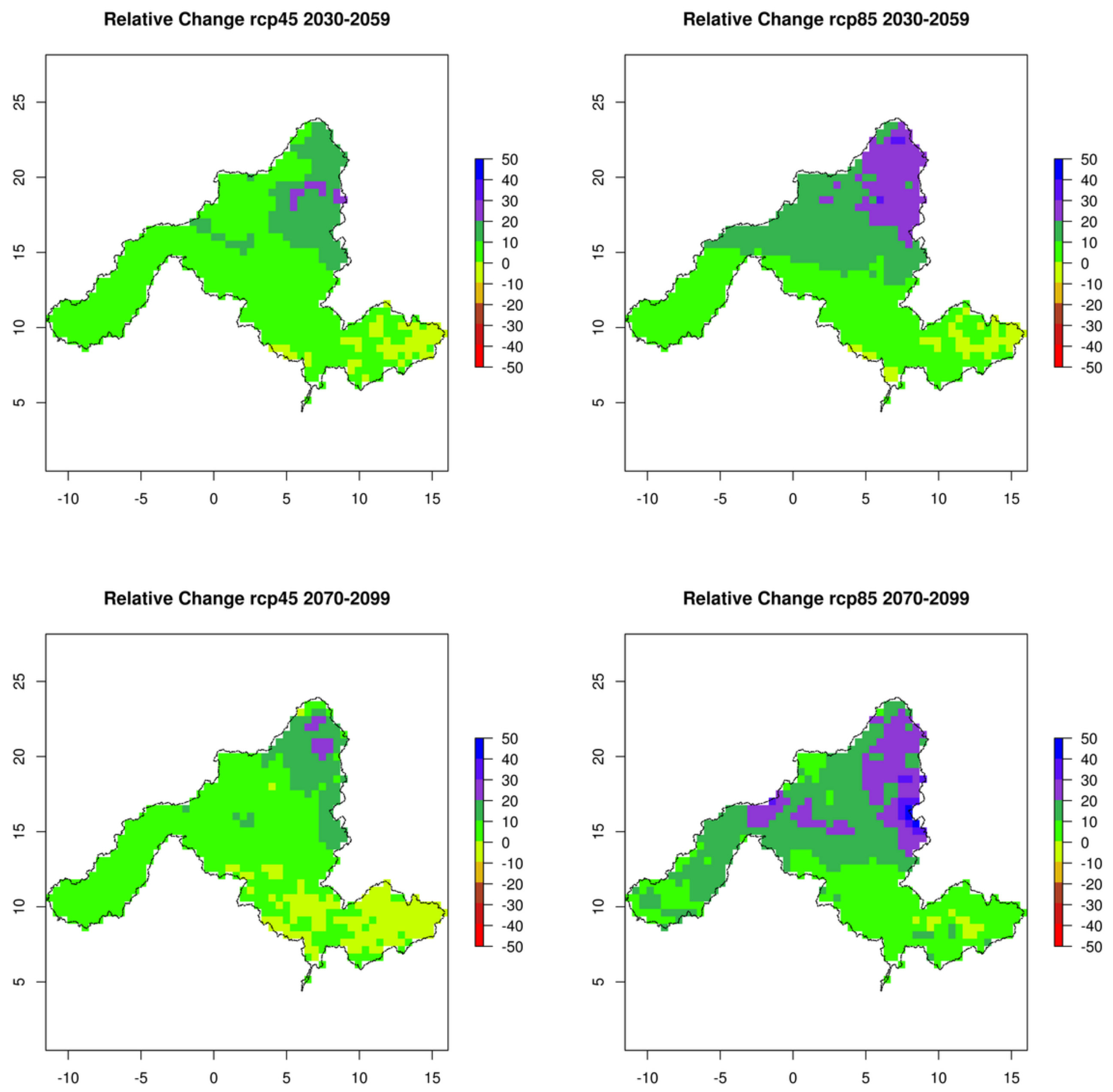



**Fig 4. 2 RCP4.5 and RCP8.5 ensemble median precipitation trends at near and far term relative to 1970-1999 in the Niger Basin.**

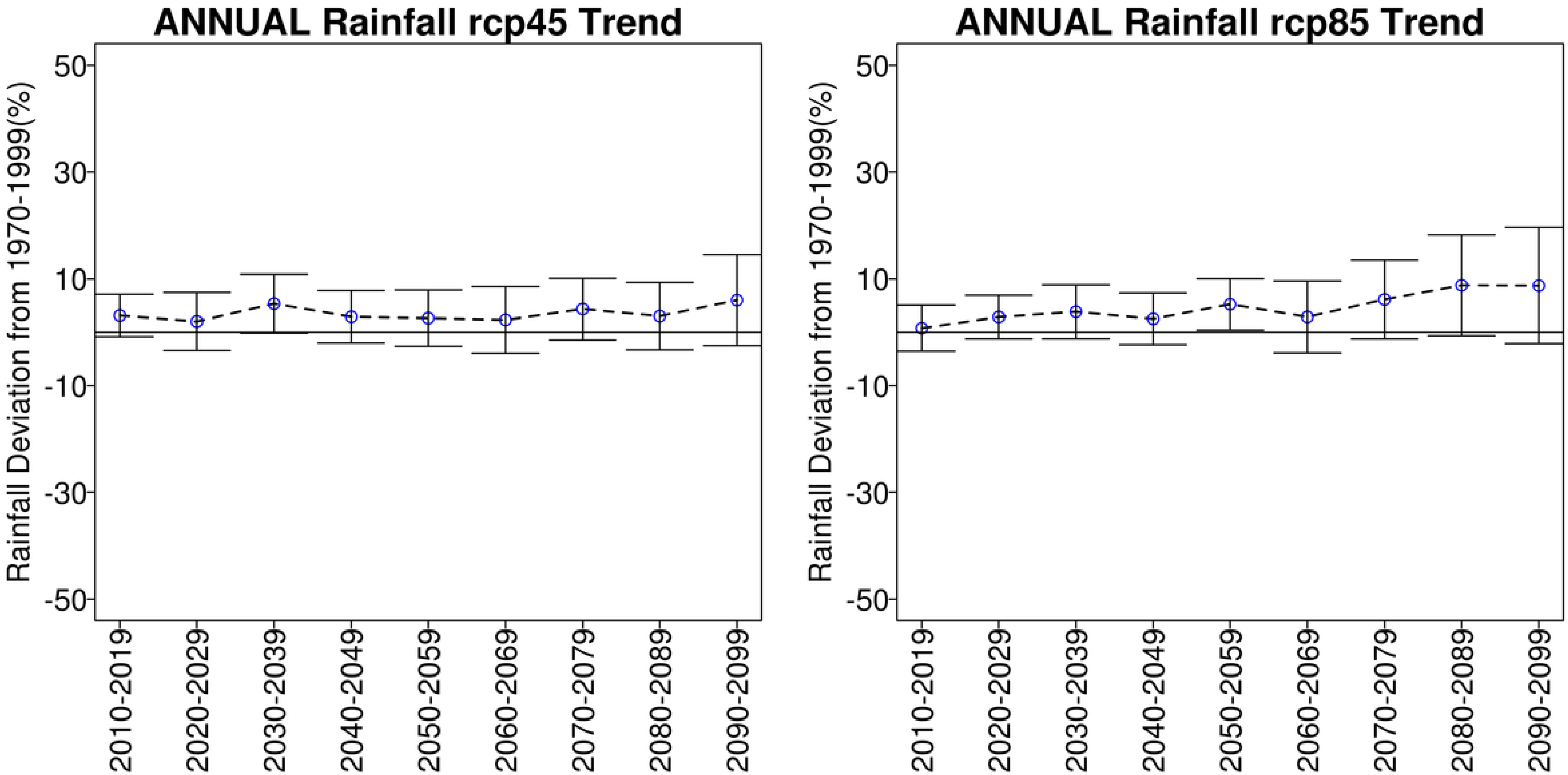



**Fig 4. 3 RCP4.5 and RCP8.5 ensemble median 21st century interannual rainfall trends relative to 1970-1999 in the Niger Basin;**

*error bars depicts mean plus and minus standard deviation respectively.*

However, under RCP4.5, DJF rainfall will experience about 10% increase at the middle of the century which gradually fades out at the end of the century. Under RCP8.5 DJF will experience about 10% decrease from middle to the end of the century. MAM precipitation projections will experience about 10% decrease at the end of the century with the RCP4.5 while no consistent trend was observed in MAM RCP8.5 rainfall projections. JJA precipitation projections will experience about 8-10% increase at the end of the century with the RCP4.5 while about 10% increase is expected in JJA rainfall under RCP8.5. SON precipitation projections will experience no change at the middle of the century while precipitation will increase to about 8-10% at the end of the century with the RCP4.5. An increase of about 5% is expected in SON rainfall at midcentury which increases to about 15-20% towards the end of the century under RCP8.5. 30 years aggregated annual and seasonal SPI presented in Fig 4.5 and 4.6 showcased an increasing annual trend (Fig 4.5) at the end of the century under the two scenarios. DJF and MAM 30 years aggregated SPI will experience decrease while an increase is expected in the JJA and SON seasons under the two emission scenarios.

### *4.3.2 Temperature and PET*

For temperature (Fig 4.7), a consistently increasing trend with high confidence is projected in the two scenarios. In the RCP4.5 scenario temperature will rise from about 5% to 10% from the beginning to the end of the century while under

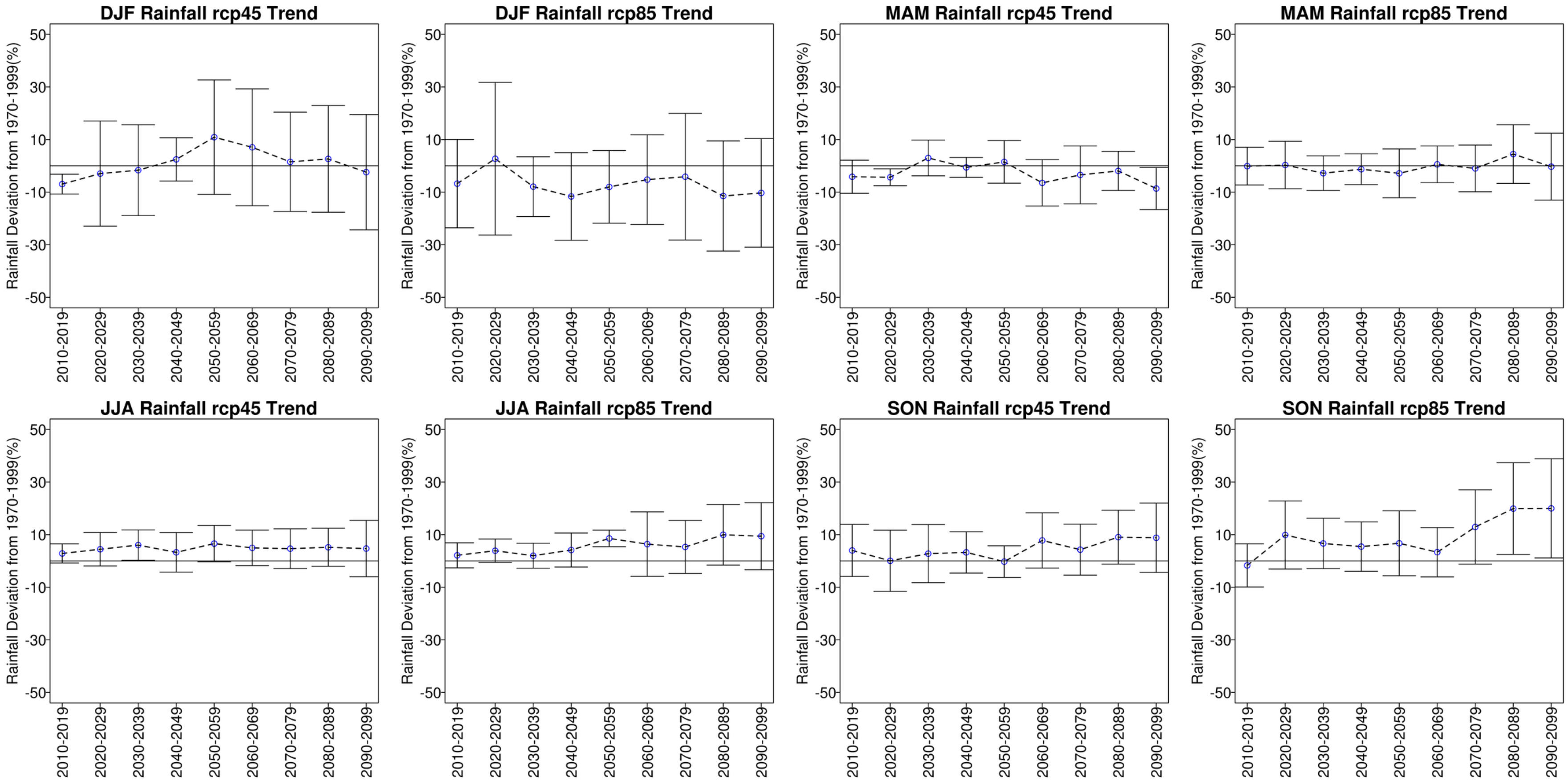



**Fig 4. 4 RCP4.5 and RCP8.5 ensemble median 21st century seasonal rainfall trends relative to 1970-1999 in the Niger Basin;**

*error bars depicts mean plus and minus standard deviation respectively.*

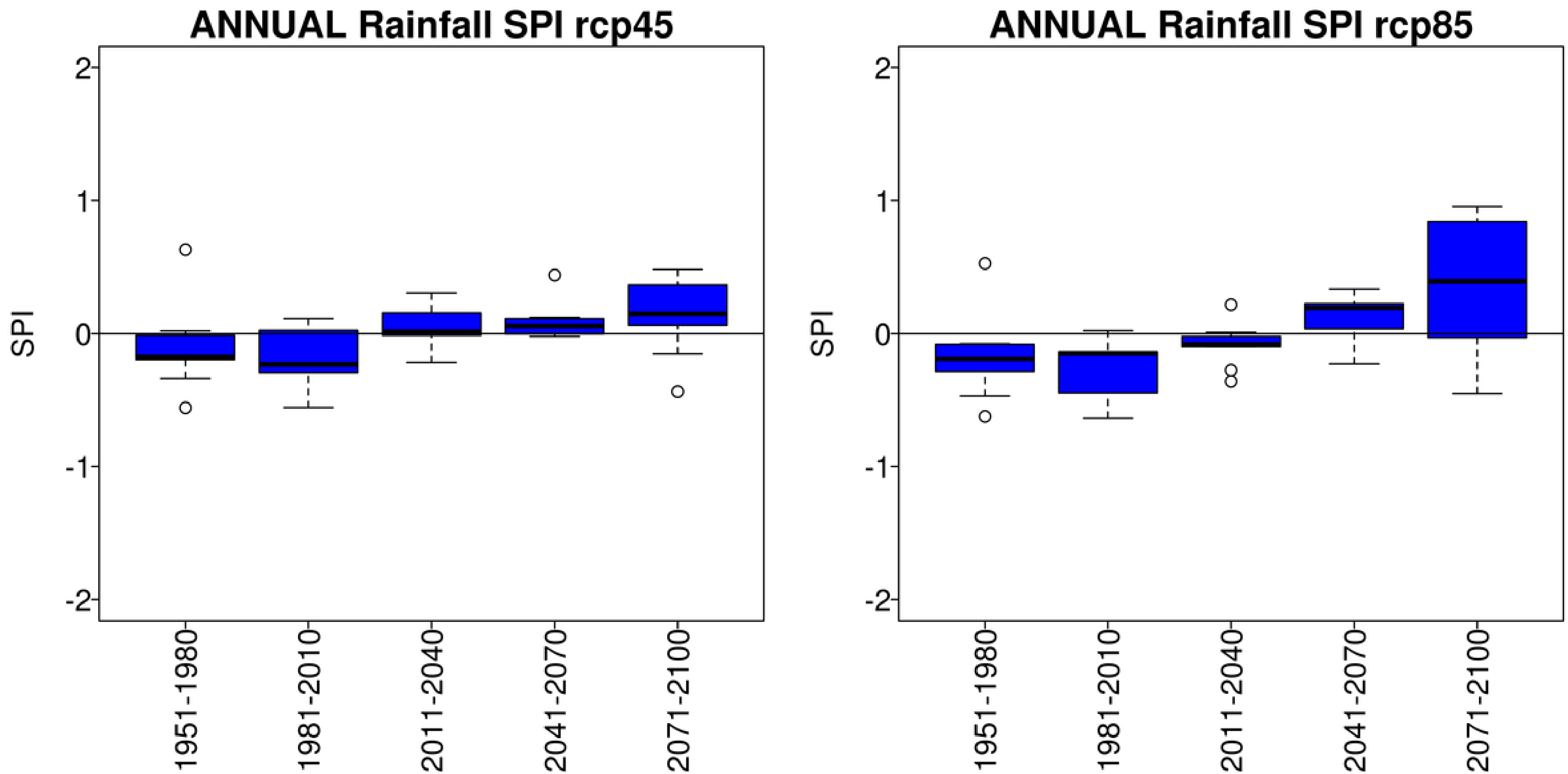



**Fig 4. 5 RCP4.5 and RCP8.5 ensemble median 21st century annual climatological SPI in the Niger Basin**

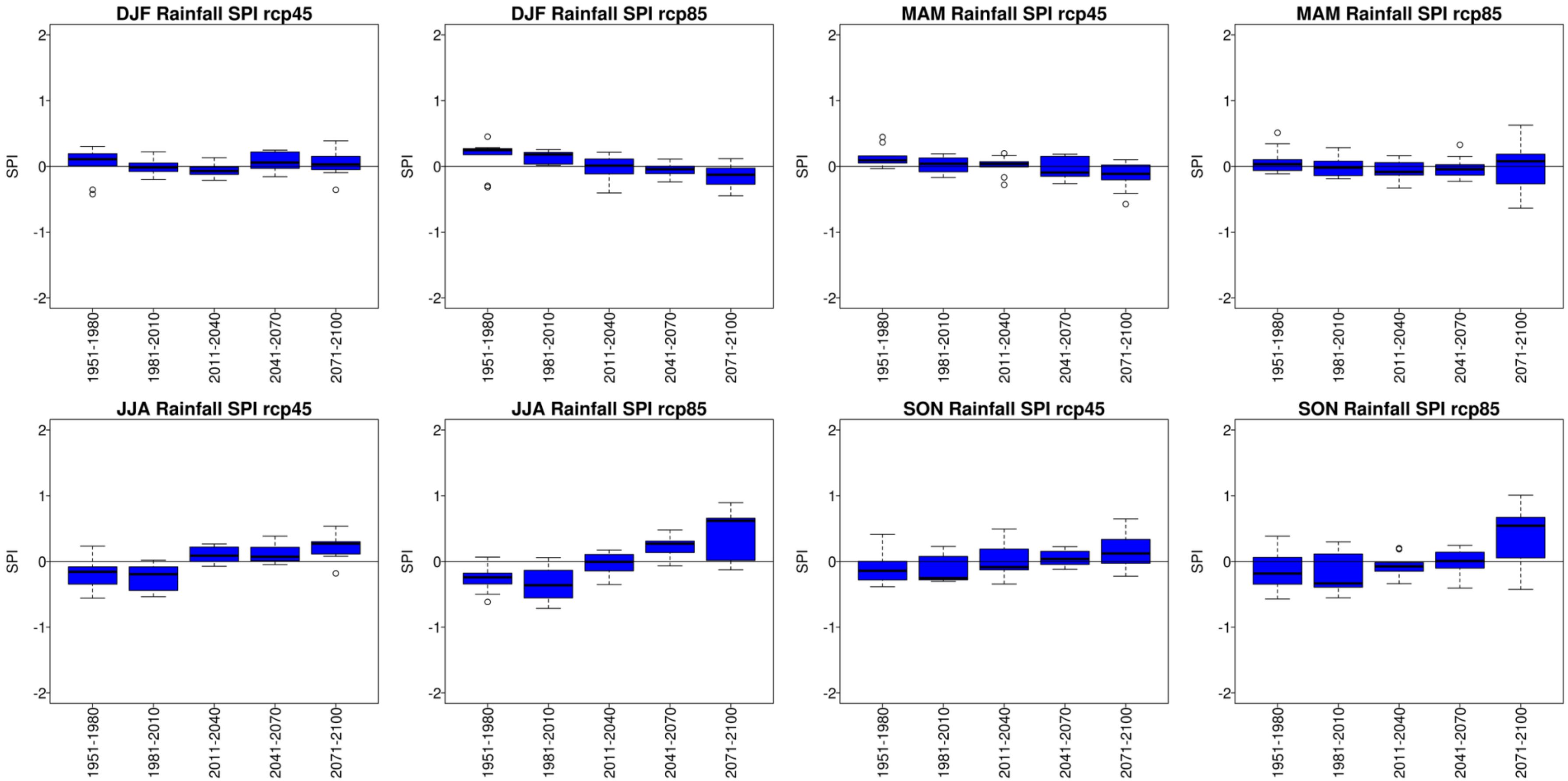



**Fig 4. 6 RCP4.5 and RCP8.5 ensemble median 21st century seasonal climatological SPI in the Niger Basin.**

RCP8.5 the Niger basin will experience about 5% to 20% increase in temperature from beginning to the end of the century. Projected seasonal temperature trends (Fig 4.8) followed the observed trends as the annual. For PET (Fig 4.7), a consistent increasing trend with high confidence is also projected in the two scenarios. In the RCP4.5 scenario PET will rise from about 10% to 20% from the beginning to the end of the century while under RCP8.5 the Niger basin will experience about 10% to 40% increase in PET from beginning to the end of the century. Projected seasonal PET trends followed the observed trends as the annual (Fig 4.9).

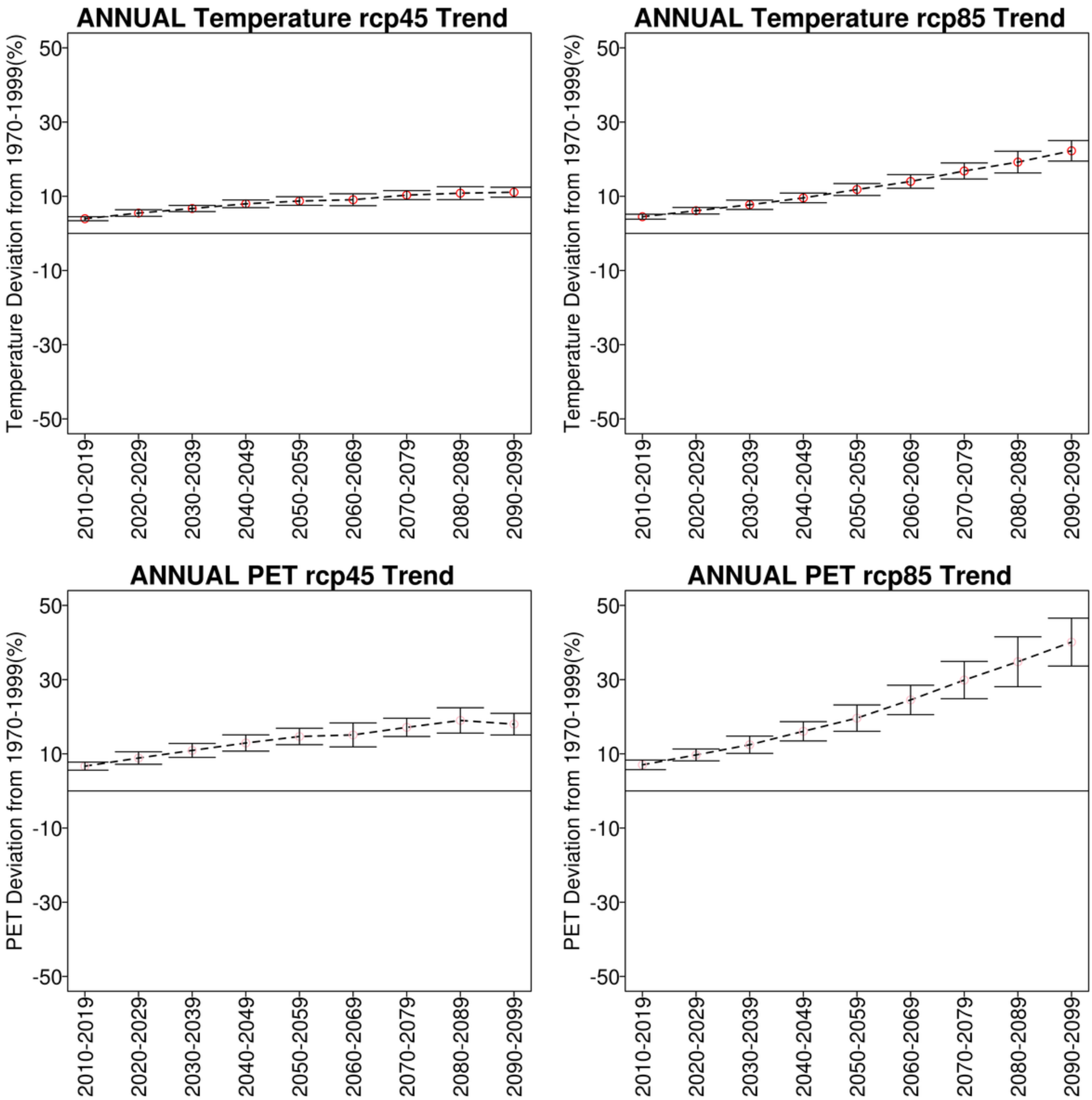



**Fig 4. 7 RCP4.5 and RCP8.5 ensemble median 21st century interannual temperature and PET trends relative to 1970-1999 in the Niger Basin;**

*error bars depicts mean plus and minus standard deviation respectively.*

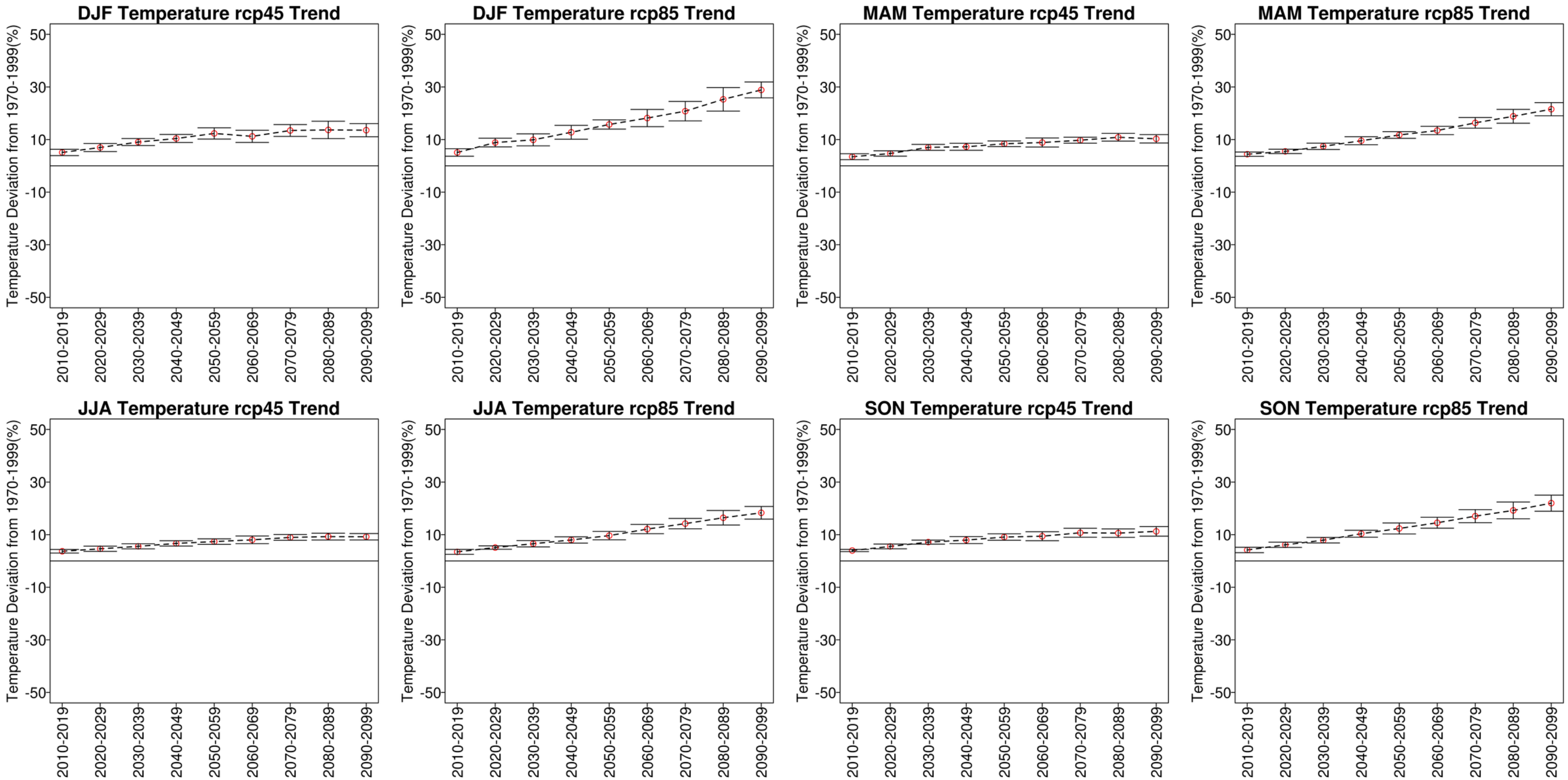



**Fig 4. 8 RCP4.5 and RCP8.5 ensemble median 21st century seasonal temperature trends relative to 1970-1999 in the Niger Basin;**

*error bars depicts mean plus and minus standard deviation respectively.*

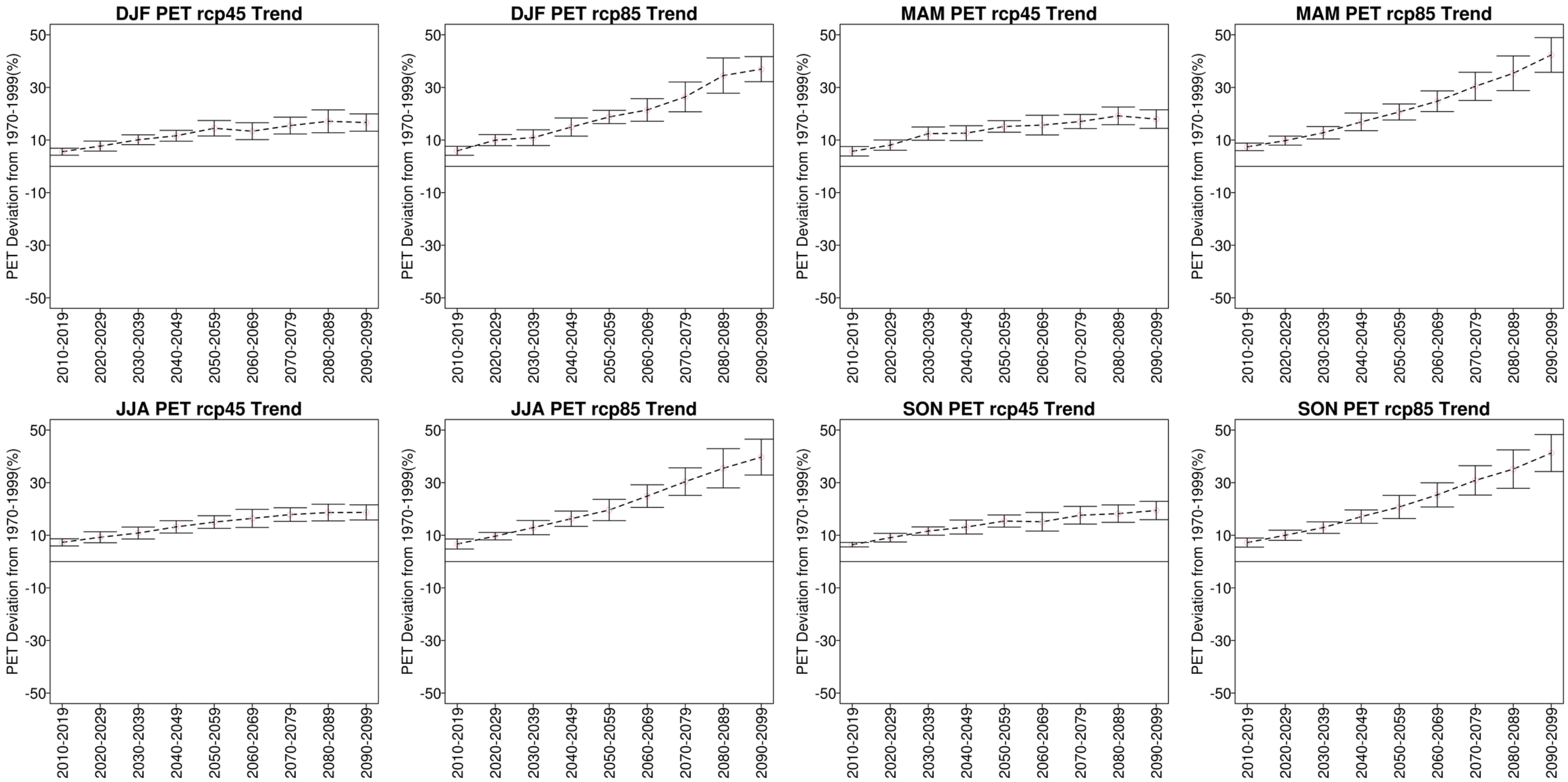



**Fig 4. 9 RCP4.5 and RCP8.5 ensemble median 21st century seasonal PET trends relative to 1970-1999 in the Niger Basin**

*error bars depicts mean plus and minus standard deviation respectively.*

### 4.4 Discussion and Conclusion

Climate change will drive increase in precipitation, temperature and PET in the Niger basin. Sahelian region will experience greater increase in rainfall compared to other ecological zones due to intensification of hydrological cycle by increasing atmospheric temperatures which results in projected severer dry seasons and wetter rainy seasons (Huntington 2006). The study also revealed that the greater the green house gas emissions, the more the hydrological perturbation as observed in the evaluated RCP4.5 and RCP8.5 emission scenarios.

Improved GCM agreements in the CMIP5 projected precipitation patterns shows higher confidence in the CMIP5 projections in the Niger basin; since there was no consistent trend in projected precipitation trends across the CMIP3 models (Druyan 2011). This is in agreement with study of Sillmann et al. (2013) who observed reduced spread amongst CMIP5 models for several temperature indices compared to CMIP3 models, despite the larger number of models participating in CMIP5. Management of hydrological projects in the Niger basin has been reported to be difficult due to high uncertainties in rainfall-runoff projections (KfW 2010). The CMIP5 archive showcased greater potentials of reducing this challenge if adequately assessed. The archive will enhance effective climate change impacts assessments for several sectors such as water resources, agriculture, energy etc, and thereby improving human security.

The decrease in DJF and MAM rainfall will influence water resources and agriculture. Redistribution of cropping calendar, irrigation and adequate water storage might be necessary to cope with the changes. Increase in JJA and SON rainfall will further aggravate the witnessed flooding in the basin due to high intensity rainfall in the period.

Increases in air temperature could further increase the vulnerability of agriculture through a yield reduction as a result of heat stress, although large discrepancies exist in yield predictions as a result of climate change in the region and the sign of change is uncertain (Roudier et al. 2011). Rise in PET more than precipitation will aggravate the challenges of increased soil moisture drought which is domiciled in the region (IPCC 2014). Therefore, it is important to derive methodologies for unveiling impacts of the climate change on water resources and other functions of the Niger basin which are addressed in chapters 5 and 6 of this dissertation. Future work should consider making projections based on ecological zones of the Niger basin which seem to behave differently.

# CHAPTER 5

## Impacts of 21st Century Climate Change on Runoff in the Niger Basin

### 5.1 Introduction

Surface water is fundamental for many sectors in West Africa (WA) including agriculture, power generation and fisheries (Roudier et al. 2014). Several studies have shown that discharge evolutions over past decades in WA have been strongly affected by rainfall variations. The rainfall changes of the 1930-1960 wet periods, the 1970-1980 droughts and the return of rainfall in the 1990s and 2000s illustrate this clearly and have demonstrated the population's vulnerability, particularly in Sahelian areas (Writeshop 2007). Climate change is expected to worsen, seriously affecting in particular the economic development as well as social welfare, the environment, natural resources and physical infrastructures. It would certainly most likely affect the way of life in the region due to low resilience capabilities as well as fragile ecosystems and even threaten global security through migratory pressures and resources conflicts.

Future climate simulations in West Africa have been a challenge for climate models due to the complexity and the diversity of processes to be represented (Laprise et al. 2013). No coherent trend for either decreasing or increasing precipitation emerges from global climate models - GCM (Druyan 2011). This lack of consensus among GCM projections was attributed to the unclear West African monsoon precipitation response to anthropogenic climate change (Biasutti and Giannini 2006; Douville et al. 2006; Giannini et al. 2008). In addition, the typical grid box of GCMs (in the range of 100–400 km) is too coarse to account for landscape heterogeneities related to vegetation, topography, soil and water resources, and coastlines, which are important for the physical response governing the local and regional climate change signal (Paeth et al. 2006; Rummukainen 2010). Regional Climate Models (RCM) can potentially overcome this limitation; however, Diallo et al. (2012) found mixed results in terms of RCMs improving the simulation of climate patterns compared to the driving GCMs.

The Niger River Basin - home to 100 million people - is a vital and complex asset for West Africa; and it has been identified with the challenges of regional climate change. In the past 50 years, reduction in rainfall of 10 to 30% in the basin has led to a deficit of 20 to 60% in river discharge (Novotny and Stefan 2007). Lebel (2003) reported a severe decrease of the river flows in the Niger basin as a result of the droughts of the 1970s. The River dried up for several weeks at Malanville in Benin Republic in 1985 as a result of a one-year lag of lowest rainfall and runoff in 1984 (Legesse et al. 2003). An analysis of selected locations in the upper and middle Niger basin shows that projections by CMIP3 GCMs and 20 AR4-models are not consistent concerning the direction of change in rainfall and runoff, making management of hydrological projects in the Niger basin difficult (KfW 2010). Several studies (Diallo et al. 2012; Ibrahim et al. 2013; Laprise et al. 2013; Mariotti et al. 2011; Oguntunde and Abiodun 2013; Panitz et al. 2013; Sylla et al. 2010) have evaluated future pattern of climate change in the region. However, most of these studies either used the CMIP3 datasets or focused on the large scale without giving finer basin scale information needed for hydrological climate change impact assessments and adaptations. This study presents ensemble CMIP5 projected impacts of climate change on runoff at Kainji and Malanville sites along the river Niger.

The objectives of the study are:

- to evaluate the effects of bias correction on CORDEX CMIP5 precipitation projections
- to model impacts of the $2^{1st}$ century climate change on runoff in Malanville (Benin) and Kainji (Nigeria) settlements along the Niger Basin

## 5.2 Materials and Methods

### *5.2.1 Study Area*

The Niger River Basin covers 2.27 million $km^2$ (Ogilvie et al. 2010) and with 4200 km in length the Niger is the third longest river in Africa. The basin consists of ten countries including some parts of Benin and Nigeria, where the study sites

(Malanville and Kainji) are located (Fig 5.1). Malanville commune (lowest administrative level in Benin) covers an area of 3016 $km^2$ and had a population of about 160000 people in 2013 (INSAE 2013). It has a mean annual precipitation of about 800 mm (based on observations from 1950 to 2010) which is concentrated in one rainy season from mid April to mid October (Oyerinde et al. 2014). During the dry season, Malanville is subject to the Sahelian northeast trade wind that comes with relatively cool and dry environmental conditions. Highest temperatures of about 46 °C are recorded in March and April while the lowest temperatures (about 16 °C) are observed in December and January, with an annual average of 28 °C based on the same observation period (Oyerinde et al. 2014).

Downstream of Malanville is the Kainji lake which resulted from a multipurpose dam project installed in 1968 (Fig 5.1). The purposes of the reservoir include power generation, progressive development of navigation, flood control in the Niger valley, and estimated fishery production of over 10000 tons annually. The reservoir has a total storage volume of 15 $km^3$ and a surface area of 1270 $km^2$ at maximum water surface elevation (Jimoh 2008). Kainji dam has eight hydropower plants with a total installed capacity of 760 MW (Jimoh 2008) and supplies 12 per cent of the total electricity of Nigeria (Mohammed et al. 2013). Since 1990, more frequent extreme events in inflow to the reservoir have led to increased downstream spill discharge, sometimes resulting in floods downstream. Such aggravated flooding was witnessed in some downstream communities in 1997 and 1998 when properties worth over 3 million USD were destroyed (Salami and Sule 2010).

### *5.2.2 Hydrological Model Description*

The model used in the present study, is a lumped parameter, conceptual rainfall-runoff model, based on unit hydrograph (Jakeman et al. 1990) which was implemented on the R package “*Hydromad*” (Andrews et al. 2011) . The model consists of two modules, a non-linear IHACRES loss module - where losses of water occur - to convert rainfall to effective rainfall. Generally the best configuration of IHACRES model in semi-arid regions or for ephemeral streams is a one store loss module with a simple linear routing model (Ye et al. 1997). Many research investigations have disclosed the superiority of the ARMAX models to simple linear models in different catchments around the World (Dutta et al. 2011). Here, the IHACRES simple linear routing model was replaced with the auto-regressive, moving average, with exogenous inputs (ARMAX) (Andrews et al. 2011; Dutta et al. 2011) to route the effective rainfall to streamflow. The loss module is defined by just five parameters, which together predict daily effective rainfall (Jakeman and Hornberger 1993) while the ARMAX routing module has an additional four parameters (Andrews 2011).

The loss module involves calculation of an index of catchment storage $s_k$, at each time step k (daily in this paper) based upon an exponentially decreasing weighting of precipitation and evapotranspiration (or temperature) conditions (Jakeman and Hornberger 1993; Ye et al. 1997). The effective rainfall $u_k$ was computed from incidence precipitation $r_k$ and the storage index $s_k$ as described below:

$s_k = cr_k + (1 - t_w^{-1})s_{k-1}$

$= c\lfloor r_k + (1 - t_w^{-1})r_{k-1} + (1 - t_w^{-1})^2 r_{k-2} + \ldots\ldots\rfloor$ EQ 1

$t_w(t_k) = t_w \, exp[(20 - t_k)f]$ EQ 2

$u_k = (s_k - l)^p r_k$ if $s_k > 0$ otherwise $s_k = 0$ EQ 3

$s_k$= catchment wetness index or antecedent precipitation index

$c$ = the increase in storage index per unit rainfall in the absence of evapotranspiration (it is not really a free parameter but merely a normalizing one)

$t_w$= is approximately the time constant, or inversely, the rate at which the catchment wetness declines in the absence of rainfall.

$t_k$ = is the temperature in degrees Celsius at time step k.

$r_k$ = incidence precipitation at time step k.

$f$ = temperature modulation factor which determines how $t_w(t_k)$ changes with temperature.

$l$ = moisture threshold for producing flow.

$p$ = power on soil moisture (above the threshold l).

During a model calibration, four of the five soil moisture parameters ($s_k$ , $c$, $f$ and $l$ ) are determined directly from the raw rainfall, streamflow and temperature data. The remaining ($p$) is calibrated using a trial and error search procedure along with the four ARMAX routing parameters (Auto-regressive terms a_1, a_2 and moving average terms b_0, b_1), optimizing the model fit to the observed daily streamflow record. Additional information on the loss module are to be found in (Jakeman and Hornberger 1993; Ye et al. 1997) while the ARMAX routing module are well described in (Andrews 2011). In this study, the optimum model parameters were obtained by an automatic calibration with the "fitByOptim" algorithm on R which selects the optimum parameters that gives the best preferred model performance statistics - here taken as Nash Coefficient (Andrews et al. 2011).

### *5.2.3 Observed Data*

The hydrological model requires daily precipitation, potential evapotranspiration (PET) and river discharge. The Global Precipitation Climatology Project (GPCP) daily precipitation (Huffman et al. 1997) and the Modern Era Retrospective-analysis for Research and Applications (MERRA) 2 meter temperature (Rienecker et al. 2011) was used for model calibration. The selection of the products was motivated first by their availability over the region of interest and the fact that they are commonly used in hydrological research studies (Gosset and Viarre 2013;

Jobard et al. 2011; Negrón Juárez et al. 2009). Catchment boundary of the Niger basin was obtained from Hydrosheds. Upstream area and boundaries of Kainji and Malanville (Figure 5.1) was delineated with a preconditioned DEM from Hydrosheds using the Hortonian drainage networks analysis (Jasiewicz and Metz 2011).

Rainfall and temperature distribution in West Africa have been attributed with the back and forth movement of the Inter Tropical Convergence Zone (ITCZ) (Lucio et al. 2012). The movement of the ITCZ follows the position of maximum surface heating associated with meridional displacement of the overhead position of the sun, lower latitudes experience higher rainfall and lower temperature, whereas higher latitudes experience lower rainfall and higher temperatures. Due to these large rainfall gradients, basin satellite rainfall and temperature series were calculated as the weighted average of all grid boxes by latitudes. For extraction of rainfall, higher latitudes were given lower weights than the lower latitudes while the reverse was applied for temperature.

We computed catchment evapotranspiration from MERRA 2 meter daily air temperature on each catchment with the Hamon model (Oudin et al. 2005).

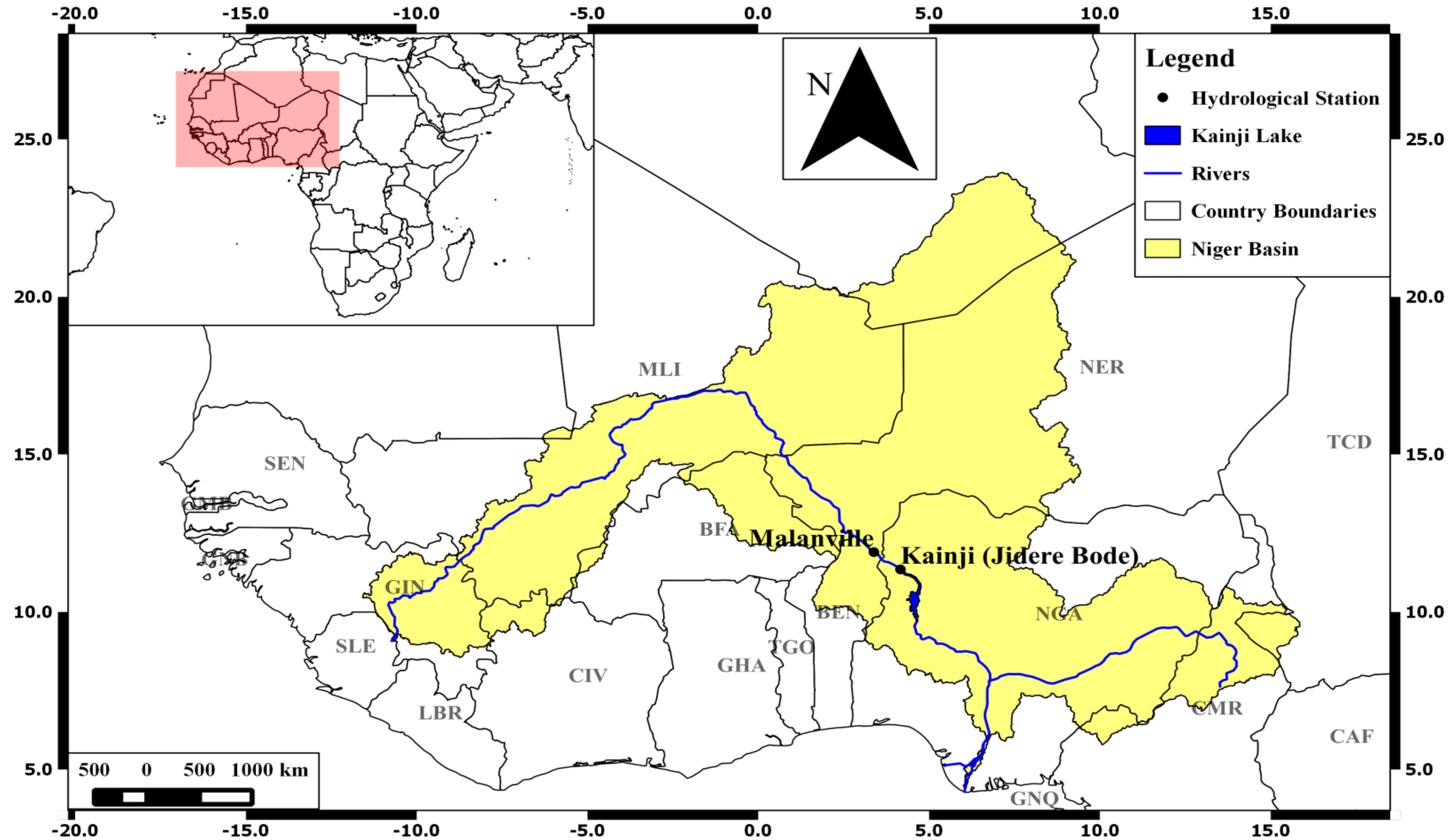



**Fig 5. 1 Location of Malanville (Benin) and Kainji Lake (Nigeria) on the Niger Basin**

This evapotranspiration model was selected based on a recent finding that very simple evapotranspiration models relying on mean daily temperature are as efficient as more complex models such as the Penman model and its variants (Oudin et al. 2005).

### *5.2.4 Future projections*

Rainfall data from a set of 8 CMIP5 GCMs (Table 5.1) with two emission scenarios was used. The GCMs were downscaled to 0.44° x 0.44° (approximately 50 km) resolution with the SMHI-RCA (Sveriges Meteorologiskaoch Hydrologiska institute) RCM within the CORDEX-Africa regional downscaling experiments. CORDEX is a program sponsored by World Climate Research Program (WCRP) to develop an improved framework for generating regional-scale climate projections for impact assessment and adaptation studies worldwide within the IPCC AR5 timeline and beyond (Giorgi et al. 2009). Climate projection framework within CORDEX is based on the set of new global model simulations planned in support of the IPCC Fifth Assessment Report, referred to as CMIP5 (Taylor et al. 2012). This set of simulations includes a large number of experiments, ranging from new greenhouse-gas scenario simulations for the 21st century, decadal prediction experiments including the carbon cycle and experiments aimed at investigating individual feedback mechanisms (Taylor et al. 2012). These simulations are based on the reference concentration pathways (RCPs), i.e. prescribed greenhouse-gas concentration pathways throughout the 21st century, corresponding to different radiative forcing stabilization levels by the year 2100. Within CMIP5, the highest-priority global model simulations have been selected to be the RCP4.5 and RCP8.5, roughly corresponding to the IPCC SRES emission scenarios B1 and A1B, respectively. The same scenarios are therefore also the highest priority CORDEX simulations (Giorgi et al. 2009). In this study, basin projection data were extracted as described in the observed (section 5.6). Future evapotranspiration was also computed from extracted temperature with the Hamon's model earlier described (section 5.6).

### *5.2.5 Evaluation and Bias Correction of RCM/GCM data*

Bias-adjustment aims at eliminating errors in the climate model data when compared against historic observations (Kling et al. 2012). It rely either on computing the difference between satellite and gauge based precipitation where gauge-based measurements are available or on a combination of several satellite-based estimates in regions with no gauges (Kling et al. 2012). We chose the well known delta-change (Kling et al. 2012) method for bias correction of temperature while quantile mapping (Bürger 2014; Maraun 2014; Maraun 2013) was used for precipitation due to some inadequacies of the delta-change method. The main criticism of the quantile mapping bias correction has been an "Inflation issue" when applied on daily data (Bürger 2014; Maraun 2014; Maraun 2013), this was minimized by conducting the mapping separately for each month. Nevertheless, we compared the original RCM/GCM and bias corrected precipitation data with the observed using six efficiency coefficients displayed in Table 5.2.

### *5.2.6 Hydrological model calibration*

Hydrological model calibration was conducted with six years (1997-2003) daily observed data at Kainji and three years (2003-2005) in Malanville while validation runs from 2004-2010 at Kainji and 2006-2008 for Malanville. The choice of the period of data was motivated by data availability and the suggestions of (Shin et al. 2013). Shin et al. (2013) disclosed that the five years may be the minimum duration of daily rainfall data needed to obtain stable IHACRES model parameters. The model was automatically calibrated for the stipulated periods (using observed data) with the optimization of the Nash efficiency. The pre-calibrated hydrological model with observed was used to predict daily runoff form 1950-2100 using projected rainfall and temperature datasets from 8 global climate models and two emission scenarios from the CORDEX-Africa regional downscaling experiments (section 5.7).

## Table 5. 1 List of CMIP5 models considered in the study

| Modeling Center (or Group) | Institute ID | Model Name | Resolution |
|---|---|---|---|
| Canadian Centre for Climate Modelling and Analysis | CCCMA | CanESM2 | T63 (;2.8125832.81258) L35 |
| Centre National de Recherches Météorologiques / Centre Européen de Recherche et Formation Avancée en Calcul Scientifique | CNRM-CERFACS | CNRM-CM5 | TL127 (256 3 128) |
| NOAA Geophysical Fluid Dynamics Laboratory | NOAA GFDL | GFDL-ESM2M | M45 (;2832.58) L24 |
| Met Office Hadley Centre (additional HadGEM2-ES realizations contributed by Instituto Nacional de Pesquisas Espaciais) | MOHC | HadGEM2-ES | N96 (;1.24831.8758) L38 |
| Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology | MIROC | MIROC5 | T85 (;1.40625831.406258) L40 |
| Max-Planck-Institut für Meteorologie (Max Planck Institute for Meteorology) | MPI-M | MPI-ESM-LR | T63 (;1.875831.8758) L47 |
| Norwegian Climate Centre | NCC | NorESM1-M | F19 (;1.875832.58) L26 |
| EC-EARTH consortium | EC-EARTH | EC-EARTH | TL159 (320 3 160) |

**Table 5. 2 Efficiency coefficients for model calibration in the Niger basin**

| **Symbol** | **Full Name and Range** | **Reference** |
|---|---|---|
| Nash | Nash-Sutcliffe Efficiency ( -Infinity <= Nash <= 1 ) | *Nash and Sutcliffe (1970)* |
| d | Index of Agreement ( 0 <= d <= 1 ) | Legates and McCabe (1999) |
| md | Modified Index of Agreement | *Krause and Boyle (2005)* |
| r | Pearson Correlation coefficient ( -1 <= r <= 1 ) | |
| R2 | Coefficient of Determination ( 0 <= R2 <= 1 ) | *Krause and Boyle (2005)* |
| KGE | Kling-Gupta efficiency ( 0 <= KGE <= 1 ) | *Kling et al. (2012)* |

## 5.3 Results

### *5.3.1 Evaluation and Bias Correction of RCM/GCM datasets*

The distribution of efficiency coefficients for comparison of the 8 GCMs simulations to the GPCP observed precipitation is presented in Figure 5.2. During monthly total comparisons at Kainji, means of 0.69(NSE), 0.91(d), 0.78 (md), 0.86(r), 0.74(R2) and 0.75(KGE) were recorded before bias correction while means of 0.80(NSE), 0.95(d), 0.83 (md), 0.90(r), 0.82(R2) and 0.88(KGE) was witnessed after bias correction. Monthly standard deviations of 0.13(NSE), 0.05(d), 0.05 (md), 0.06(r), 0.10(R2) and 0.14(KGE) were recorded before bias correction while standard deviations of 0.06(NSE), 0.01(d), 0.02 (md), 0.02(r), 0.04(R2) and 0.05(KGE) was observed after bias correction. Effects of bias correction on projected discharge of the 8 GCMs are presented in Figure 5. 3. Model CCCma-CanESM2 underestimated the discharge at Kainji and this was corrected in the bias corrected projections under the two RCPs. Similar patterns of improvements in bias corrected precipitation witnessed and reported in Kainji were observed at Malanville (not presented).

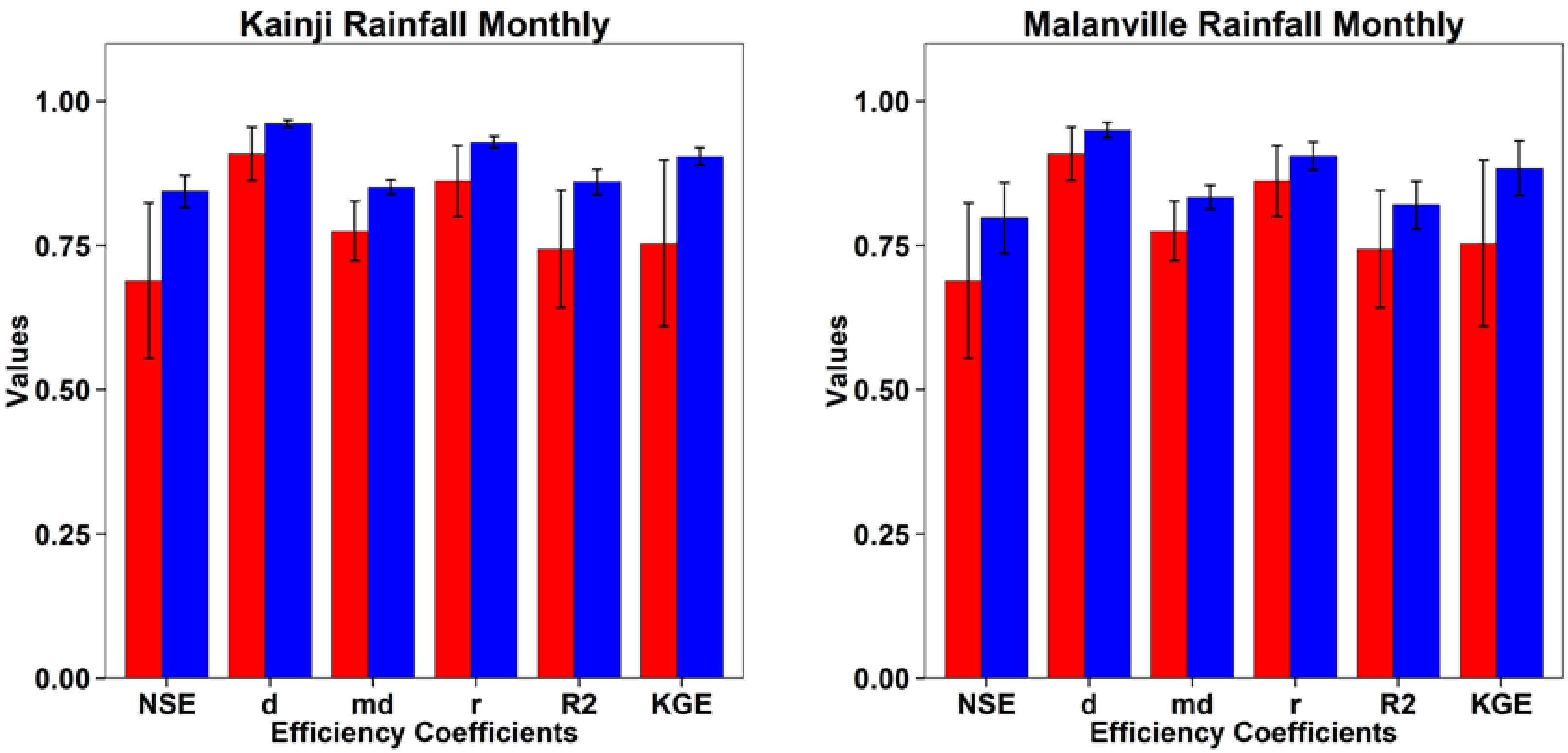
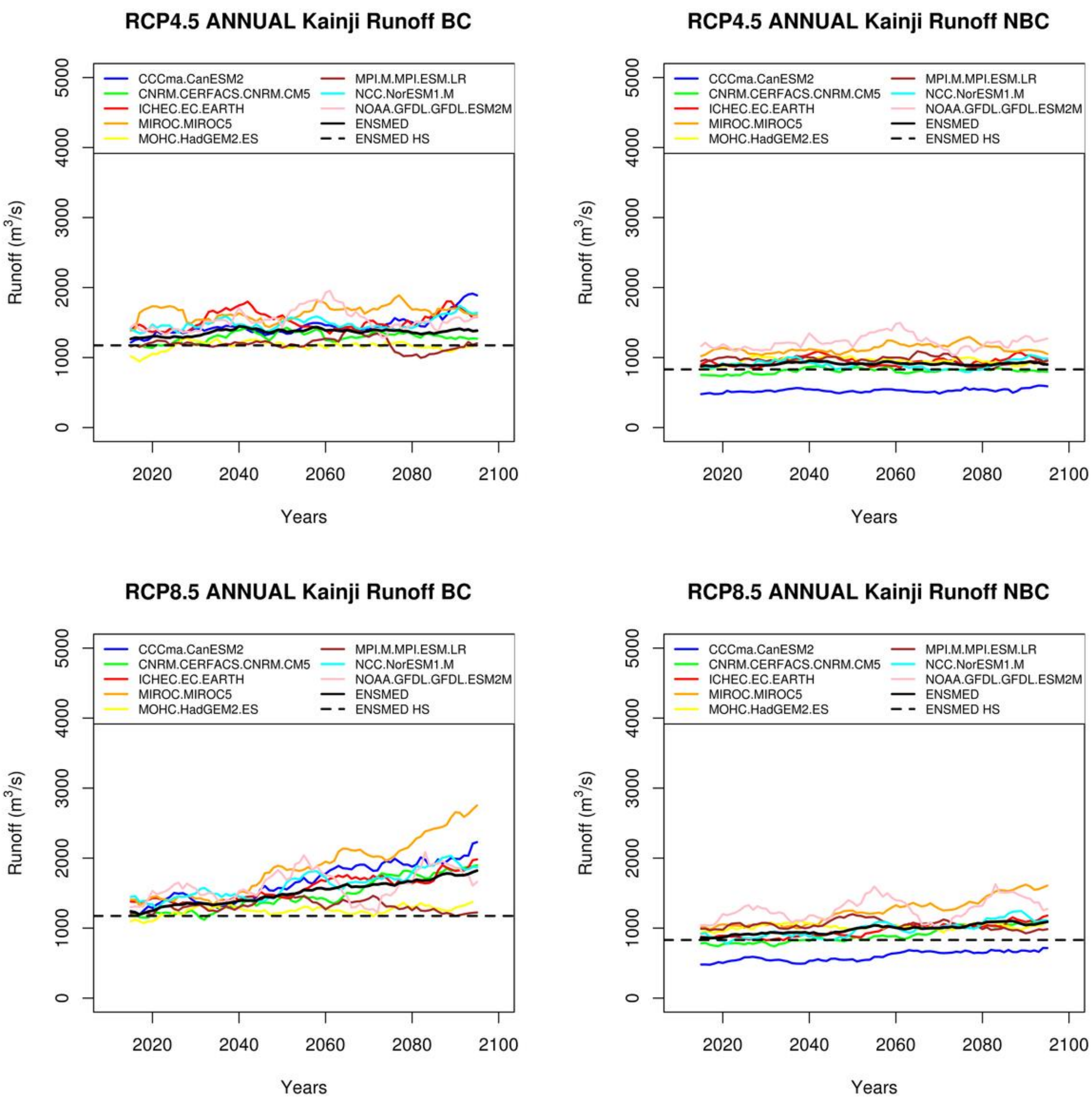



**Fig 5. 2 Efficiency coefficients of simulated precipitation by 8 GCMs compared to GPCP observed;**

*bar charts are the means while errors bars show the standard deviations respectively.*




## Fig 5. 3 Effects of Bias Correction on Ensemble Projected Discharge

### *5.3.2 Hydrological Model Evaluation*

Table 5.3 presents optimum calibration and validation efficiency coefficients recorded during hydrological model calibration at the two locations. High values of efficiency coefficients were recorded at both locations during model calibration and validation. This implies that the model could be used for hydrological projections in the two locations.

### 5.3.3 Projected Trends

### *5.3.4 Rainfall and evapotranspiration*

Annual projected rainfall, temperature and PET ensemble median from 8 GCMs for upstream the Kainji Lake is displayed in Figures 5.4. In the RCP8.5 scenario, there will be above 100mm increase in ensemble median annual rainfall upstream the Kainji Lake while under RCP4.5 the upstream area will witness slight increase to mid-century which will be lost at the end of the century. For temperature, upstream Kainji Lake will go through about 5°C increase in ensemble median average annual temperature in the 21$^{st}$ century under RCP8.5 while RCP4.5 will be attributed with about 2°C increase that will stabilize at the mid century. In the RCP8.5 scenario, there will be above 2mm increase in ensemble median annual average PET upstream the Kainji Lake while under RCP4.5 the upstream area will witness about 0.5 mm increase to mid-century which be stabilized at the mid century. Similar 21st century rainfall, temperature and PET trends are adhered with upstream area of Malanville in Benin under the two emission scenarios (not presented).

#### *5.3.5 Runoff*

Annual and seasonal (JJAS) projected runoff patterns at Kainji and Malanville from 8 GCMs are displayed in Figure 5.5 and 5.6 respectively. In the RCP8.5 scenario, there will be more than 500m$^3$ increase in annual average runoff at Kainji while RCP4.5 will be attributed with about 200m$^3$ increases through mid to the end of the century. At Malanville, the RCP8.5 scenario will be attributed with about 300m$^3$ increases in annual average runoff while RCP4.5 will be attributed with about 200m$^3$ increases through mid to the end of the century. MAM runoff will go through about 50m$^3$ at Kainji under RCP8.5 while no visible trend is observed under the RCP4.5 simulations. At Malanville MAM runoff will experience slight increase at the end of the century under RCP8.5 and there is no clear trend in the RCP4.5 scenario. JJA runoff will go through an increase of about 100m$^3$ at Kainji till the mid century under RCP8.5 while no consistent trend is observed under the RCP4.5 simulations. At Malanville JJA runoff will pass through an increase of about 50m$^3$ at the mid century under RCP8.5 and there is no clear trend in the RCP4.5 scenario.

The largest runoff increase will be experienced in the SON season under the two emission scenarios. SON runoff will go through an increase of about 1000$m^3$ and 400$m^3$ at Kainji under RCP8.5 and RCP4.5 respectively while at Malanville, SON runoff will go through an increase of about 700$m^3$ and 300$m^3$ under RCP8.5 and RCP4.5. DJF runoff will go through an increase of about 700$m^3$ and 200$m^3$ at Kainji under RCP8.5 and RCP4.5 respectively while at Malanville, SON runoff will go through an increase of about 400$m^3$ and 100$m^3$ under RCP8.5 and RCP4.5 emission scenario.

**Table 5. 3 Hydrological model calibration and validation at Kainji and Malanville**

| Efficiency Coefficients | Calibration | | Validation | |
|---|---|---|---|---|
| | Kainji | Malanville | Kainji | Malanville |
| **NSE** | 0.75 | 0.70 | 0.61 | 0.68 |
| **d** | 0.93 | 0.92 | 0.90 | 0.90 |
| **md** | 0.77 | 0.77 | 0.72 | 0.74 |
| **r** | 0.87 | 0.86 | 0.81 | 0.83 |
| **$R^2$** | 0.76 | 0.74 | 0.65 | 0.69 |
| **KGE** | 0.85 | 0.83 | 0.80 | 0.76 |

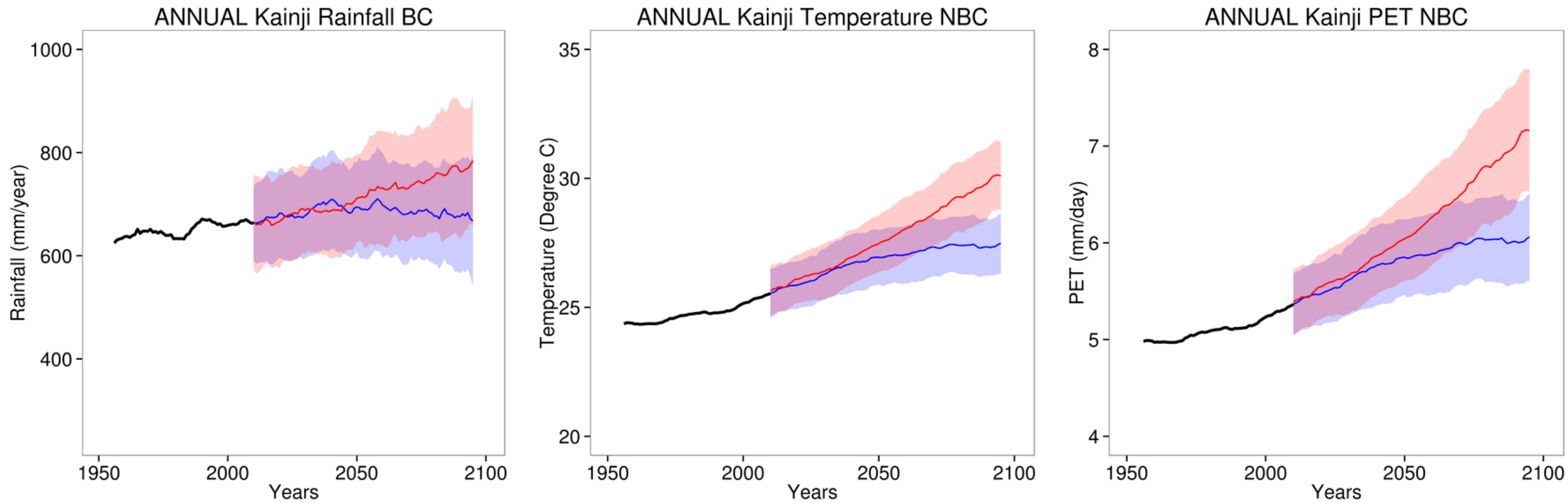



**Fig 5. 4 Ensemble median (8 GCMs) projected climate trends at Kainji;**

*black lines represents the historical, red lines are RCP8.5 ,blue lines are RCP4.5 and their respective standard deviations are showcased in surrounding bounds, BC represents bias corrected and NBC implies non bias corrected.*

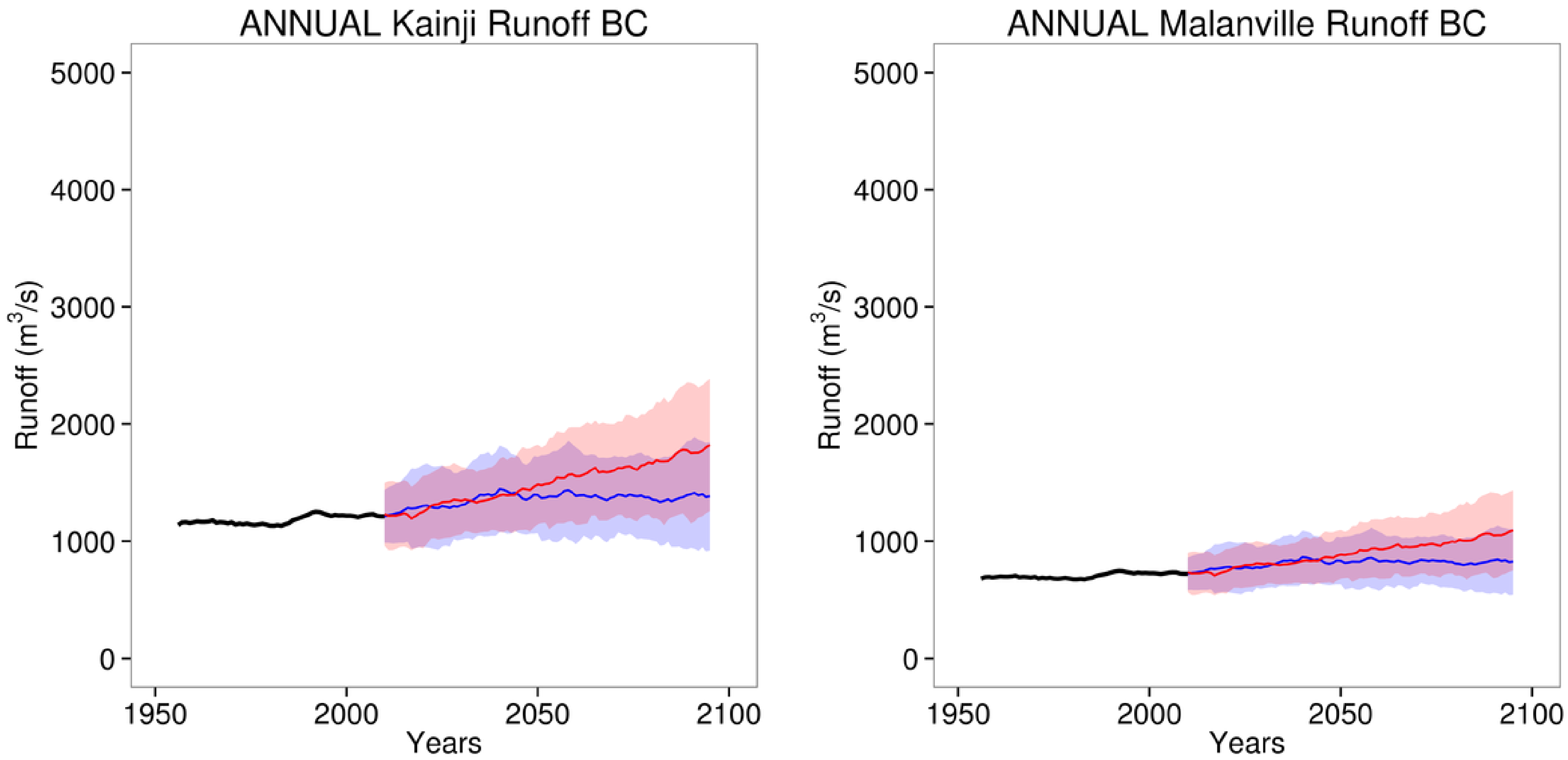



**Fig 5. 5 Ensemble median (8 GCMs) projected annual runoff trends at Kainji and Malanville;**

*black lines represents the historical, red lines are RCP8.5 ,blue lines are RCP4.5 and their respective standard deviations are showcased in surrounding bounds, BC represents bias corrected and NBC implies non bias corrected.*

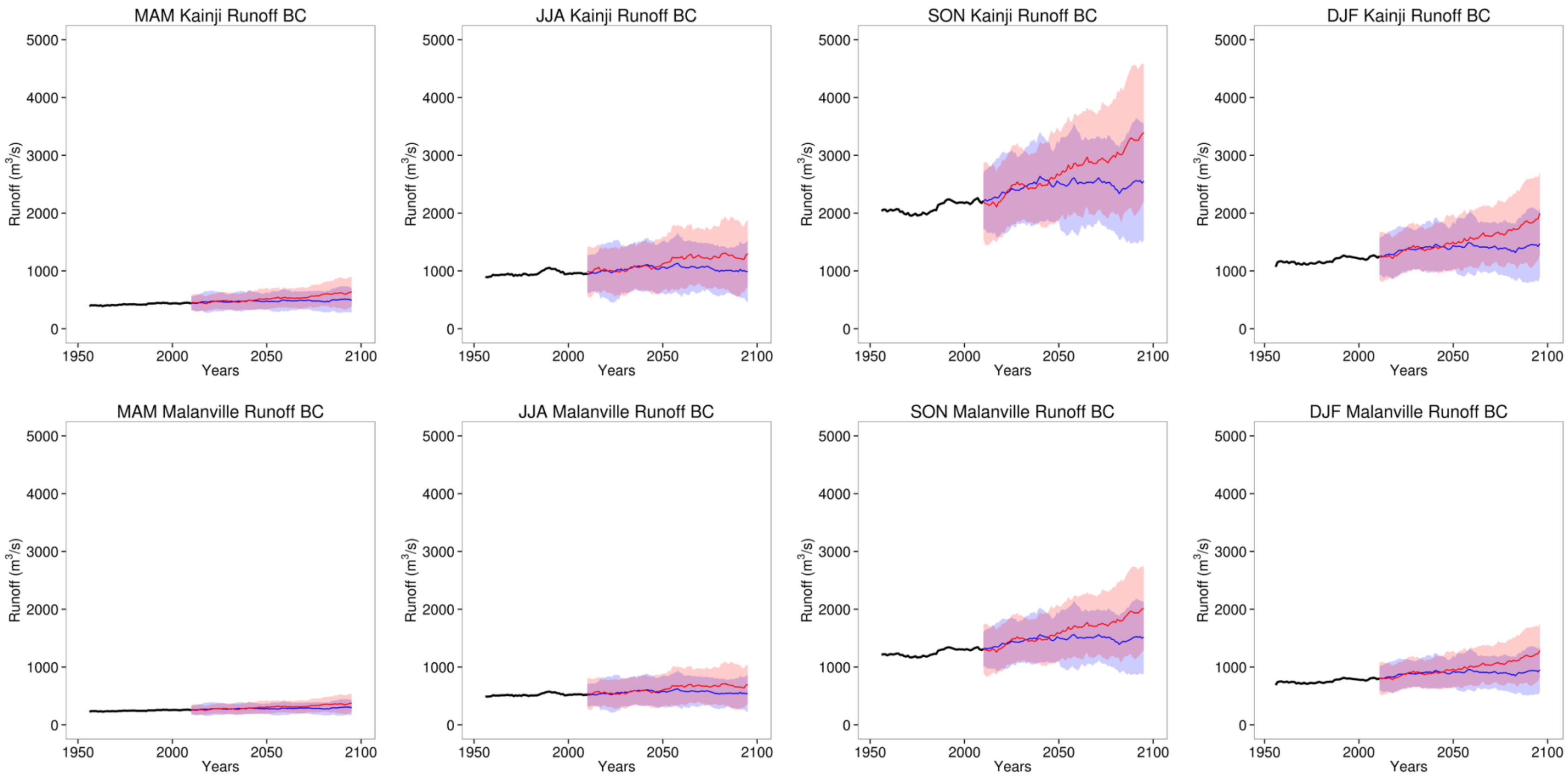



**Fig 5. 6 Ensemble median (8 GCMs) projected seasonal runoff trends at Kainji and Malanville;**

*black lines represents the historical, red lines are RCP8.5 ,blue lines are RCP4.5 and their respective standard deviations are showcased in the surrounding bounds, BC represents bias corrected and NBC implies non bias corrected.*

## 5.4 Discussion and Conclusions

Improvements of climate model projected rainfall in the evaluated catchment by quantile mapping reveals the suitability of the approach in precipitation bias correction in the Niger basin. The approach was able to improve the correlations (tested with six efficiency coefficients) between the observed and simulated rainfall in the historical period. The spread of the projections (rainfall and runoff) across the models were also reduced. Precipitation, which is the most critical variable for hydrological applications, is a very difficult variable to simulate in climate models. Most climate models, for example, tend to overestimate the amount of "drizzle" (Perkins et al. 2007; Sun et al. 2006). As a result, climate model output typically has a bias compared to observations that should be corrected for (Lenderink et al. 2007). Several ways exist to do this ( e.g., Hay et al. 2002; Leander and Buishand 2007; Kling et al. 2012). The non-linear correction applied in this study, have been used in correcting climate model biases in several spatial and temporal applications and similar results were reported (Bürger 2014; Maraun 2014; Maraun 2013).

The improved IHACRES hydrological model proposed in this study is a lumped parameter, conceptual rainfall-runoff model, based on unit hydrograph (Jakeman et al. 1990). The efficiency of the adapted hydrological model was investigated by comparing simulated streamflow with the observed.  As atmospheric forcing for all models, downscaled re-analysis data (i.e., atmospheric model output combined with observations) was used. This dataset was shown to cause relatively poor modeling efficiencies for hydrological models in the region (Gosset and Viarre 2013). Here, results showed that the adapted IHACRES model effectively simulated river discharge with downscaled re-analysis data and gives possibility for applications in poorly gauged basins that are rampant in the region. Application of the model is easier because it requires only precipitation and evapotranspiration as input data, and only little computation and calibration time.

Climate change will drive increase in precipitation, temperature, PET and runoff at Kainji and Malanville. This will be due to large pattern of increase in rainfall in Sahelian region (Chapter 4) due to intensification of hydrological cycle by increasing atmospheric temperatures which consequently increases runoff in the evaluated catchments. The study also revealed that the greater the green house gas emissions, the more the hydrological perturbation as observed in the evaluated RCP4.5 and RCP8.5 emission scenarios. Increases in air temperature could further increase the vulnerability of agriculture through a yield reduction as a result of heat stress, although large discrepancies exist in yield predictions as a result of climate change in the region and the sign of change is uncertain (Roudier et al. 2011). Rise in PET more than precipitation will aggravate the challenges of increased soil moisture drought which is domiciled in the region (IPCC 2014). Further research should aim at deriving methodologies for unveiling impacts of the climate change on water users such as energy production in the Niger basin which is the main focus of chapter 6.

# CHAPTER 6

## Impacts of Climate Change on Hydropower Production in the Niger Basin

### 6.1 Introduction

For several decades, most West African countries have suffered from electricity shortages, which constitute a serious handicap for their socio-economic development (Gnansounou et al. 2007). The situation has worsened during the last years due to human activities and climate change. Among other sources of energy; natural gas, bio-fuel, wind, solar, etc, hydropower is found to be of highest grade of energy (Abdulkadir et al. 2013). Continuation of the use of fossil fuels is set to face multiple challenges that include: depletion of fossil fuel reserves and other environmental concerns, geopolitical and military conflicts as well as instability in fuel prices. The aim of harnessing hydropower and other renewable energy are to focus on provision of sustainable energy to the economically subjugated fraction of the society, combat energy shortage and provide clean energy from the perspective of the Kyoto directive towards global decarbonization (Mohammed et al. 2013).

Hydroelectricity comes from the conversion of potential energy of water through turbines and electric generator system (Abdulkadir et al. 2013). Electricity generation from hydropower makes a substantial contribution to meeting today's increasing world electricity demands. However, only about 4 per cent of Africa's technically feasible hydro-potential has been developed, and enormous efforts are now being made across the African continent to create an 'enabling environment' for private investment; this is regarded as the only hope for developments on a large scale (Bartle 2002).

In line with the above, countries in the Niger River basin (West Africa) plan the investment of $200 million in the installation of an additional 400MW of hydropower in the nearest future, adding to the existing 685MW (Oyerinde and Wisser 2014). With the impacts of climate change in the basin already occurring, there is a need for comprehending the influence of future hydro-climatic changes on water resources and hydro-power generation in the basin. This study uses a hydrological model to simulate river flow under present and future conditions and evaluates the impacts of potential changes on electricity production of the largest hydroelectric dam (Kainji) in the Niger Basin. The Kainji dam produces 12 per cent of the current energy needs of Nigeria and was subject to large fluctuations in energy production as a result of variable inflow and other operational reasons. The objectives of the study are to:

- Develop a hydroelectricity production model for the Niger basin: case study of the Kainji lake.
- Modeling impacts of climate change on hydrological properties and hydropower production in the Niger basin.

## 6.2 Materials and Methods

### *6.2.1 Study Area*

The Niger River Basin covers 2.27 million $km^2$, with the active drainage area comprising less than 50% of the total (Ogilvie et al. 2010). At 4200 km in length, the Niger is the third longest river in Africa and the world's ninth largest river system. Two flooding regimes are prominent in the Middle and Lower Niger; during the months of May to October, rainfalls in the northern parts of Benin and south of Niamey produce floods that quickly reach Kainji with a peak flow of 4,000 to 6,000 $m^3/s$. This floodwater is laden with silt and clay sediments and is of high turbidity. Due to its color, it is referred to as the "White Flood". The second flood originates from the river's headwater region of high annual rainfall in the Fouta Djallon highlands in Guinea, and passes through the sub-arid region and deltaic swamps around Timbuktu (Mali). In these areas it loses part of its silt load before it reaches middle and lower part of the basin in November with a peak flow of about 2,000 $m^3/s$. The water is relatively clear due to its low silt load and is thus locally called the "Black Flood"(Mbagwu et al. 2000).

The Kainji lake is the largest hydropower dam on the basin and resulted from a multipurpose dam project installed in 1968 (Fig 6.1). The purposes of the reservoir include power generation, progressive development of navigation, flood control in the Niger valley, and estimated fishery production of over

10000 tons annually. The reservoir has a total storage volume of 15 $km^3$ and a surface area of 1270 $km^2$ at maximum water surface elevation (Jimoh 2008). Kainji dam has eight hydropower plants with a total installed capacity of 760 MW (Jimoh 2008) and supplies 12 per cent of the total electricity of Nigeria (Mohammed et al. 2013). The reservoir storage at Kainji relies mainly on the two earlier described flooding regimes (White and Black floods).

### *6.2.2 Hydrological Model Description*

The model used in the present study, is a lumped parameter, conceptual rainfall-runoff model, based on unit hydrograph (Jakeman et al. 1990) which was implemented on the R package "*Hydromad*" (Andrews et al. 2011) . The model consists of two modules, a non-linear IHACRES loss module - where losses of water occur - to convert rainfall to effective rainfall. Generally the best configuration of IHACRES model in semi-arid regions or for ephemeral streams is a one store loss module with a simple linear routing model (Ye et al. 1997). Many research investigations have disclosed the superiority of the auto-regressive, moving average, with exogenous inputs (ARMAX) models to simple linear models in different catchments around the World (Dutta et al. 2011). Here, the IHACRES simple linear routing model was replaced with ARMAX (Andrews et al. 2011) to route the effective rainfall to streamflow. The loss module is defined by just five parameters, which together predict daily effective rainfall (Jakeman and Hornberger 1993) while the ARMAX routing module has an additional four parameters (Andrews 2011).

The loss module involves calculation of an index of catchment storage $s_k$, at each time step k (daily in this paper) based upon an exponentially decreasing weighting of precipitation and evapotranspiration (or temperature) conditions (Jakeman and Hornberger 1993; Ye et al. 1997). The effective rainfall $u_k$ was computed from incidence precipitation $r_k$ and the storage index $s_k$ as described below:

$$
\begin{cases}
s_k = cr_k + (1 - t_w^{-1})s_{k-1} \\
= c\lfloor r_k + (1 - t_w^{-1})r_{k-1} + (1 - t_w^{-1})^2 r_{k-2} + \ldots\ldots \rfloor & \text{EQ 1} \\
t_w(t_k) = t_w\, exp[(20 - t_k)f] & \text{EQ 2}
\end{cases}
$$

$$u_k = (s_k - l)^p r_k \qquad \text{if } s_k > 0 \text{ otherwise } s_k = 0 \qquad \text{EQ 3}$$

$s_k$= catchment wetness index or antecedent precipitation index

$c$ = the increase in storage index per unit rainfall in the absence of evapotranspiration (It is not really a free parameter but merely a normalizing one)

$t_w$= is approximately the time constant, or inversely, the rate at which the catchment wetness declines in the absence of rainfall.

$t_k$ = is the temperature in degrees Celsius at time step k.

$r_k$ = incidence precipitation at time step k.

$f$ = temperature modulation factor which determines how $t_w(t_k)$ changes with temperature.

$l$ = moisture threshold for producing flow.

$p$ = power on soil moisture (above the threshold l).

During a model calibration, four of the five soil moisture parameters ($s_k$ , $c$, $f$ and $l$ ) are determined directly from the raw rainfall, streamflow and temperature data. The remaining ($p$) is calibrated using a trial and error search procedure along with the four ARMAX routing parameters (Auto-regressive terms a_1, a_2 and moving average terms b_0, b_1), optimizing the model fit to the observed daily streamflow record. Additional information on the loss module are to be found in (Jakeman and Hornberger 1993; Ye et al. 1997) while the ARMAX routing module are well described in (Andrews 2011). In this study, the optimum model parameters were obtained by an automatic calibration with the "fitByOptim" algorithm on R which selects the optimum parameters that gives the best preferred model performance statistics - here taken as Nash Coefficient (Andrews et al. 2011).

### *6.2.3 Hydropower Model Development*

Daily hydrological data (reservoir inflow, reservoir release, and reservoir level) of the Kainji reservoir were obtained from Kainji Hydroelectric PLC from 2001-2010. These were used to develop a simple hydroelectricity production model to simulate future energy production for the Kainji reservoir (Fig 6.1). The hydropower model is described below:

The water balance of the reservoir was modeled as:

$$S_{t+1} = S_t + (I_t - D_t) \qquad \text{(EQ 3)}$$

S is the reservoir storage at time t

I is the reservoir inflow

D is amount of water released out of the reservoir to the turbines

D was calculated by simulating the reservoir management of the dam with the proposed approach of Alexander et al. (2013).

The rule consists of two segments:

1) Rule at reservoir storage below optimal level (80 % full) - Logarithmic behavior

$$D = D_{min} + \ln(kS^{\propto} + 1) \ at\ S < S_{optimal} \qquad \text{(EQ 4)}$$

2) Rule at reservoir storage above optimal level (80 % full) - Exponential behavior

$$D = \exp\left(b\left(S - S_{optimal}\right)^2\right) at\, S \geq S_{optimal} \qquad \text{(EQ 5)}$$

$D_{min}$ = Minimum allowed reservoir release (20 % of average annual discharge).

S = Reservoir storage

$$k = \frac{1}{S_{optimal}{}^{\propto}}\left[exp(1 - D_{min}) - 1\right] \qquad \text{(EQ 6)}$$

b and α are model parameters that were optimized manually.

Reservoir level of the dam was estimated from reservoir storage as described below and this was used to calibrate the model by comparing modeled to observed reservoir level:

$$Reservoir\ level = \frac{Storage}{Area} \qquad \text{(EQ 7)}$$

Energy production was calculated from the simulated reservoir level using hydropower equation:

$$P = e\rho Qgh \qquad \text{(EQ 8)}$$

Where:

$P$ is power in watts.

$e$ is the dimensionless efficiency of the turbine (taken as 80% of installed capacity).

$\rho$ is the density of water in kilograms per cubic meter.

$Q$ is the inflow into the turbine (D).

$g$ is the acceleration due to gravity.

$h$ is the water level.

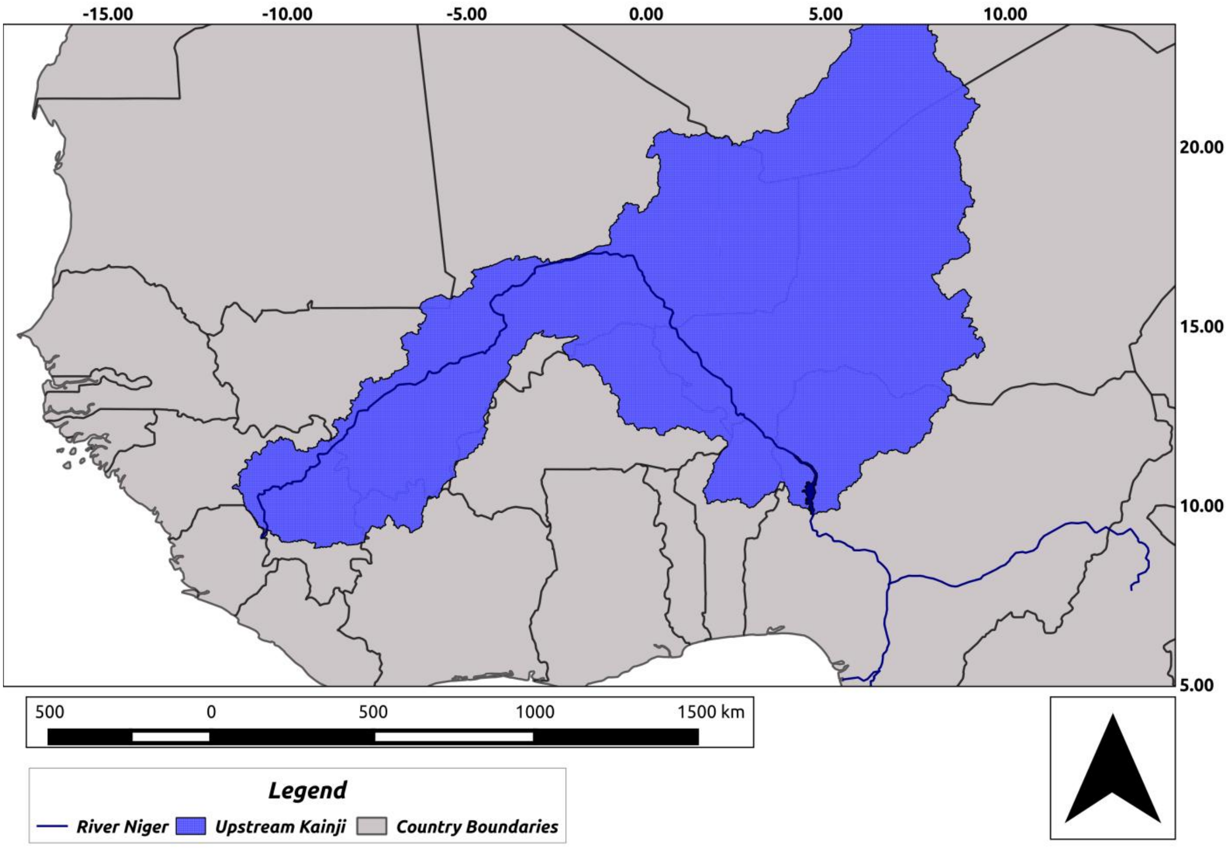



**Fig 6. 1 Upstream Area of the Kanji Lake**

### *6.2.4 Observed Data*

The hydrological model requires daily precipitation, potential evapotranspiration (PET) and river discharge. The Global Precipitation Climatology Project (GPCP) daily precipitation (Huffman et al. 1997) and the Modern Era Retrospective-analysis for Research and Applications (MERRA) 2 meter temperature (Rienecker et al. 2011) was used for model calibration. The selection of the products was motivated first by their availability over the region of interest and the fact that they are commonly used in hydrological research studies (Gosset and Viarre 2013; Jobard et al. 2011; Negrón Juárez et al. 2009). Catchment boundary of the Niger basin was obtained from Hydrosheds. Upstream area and boundaries of kainji (Figure 6.1) was delineated with a preconditioned DEM from Hydrosheds using the Hortonian drainage networks analysis (Jasiewicz and Metz 2011).

Rainfall and temperature distribution in West Africa have been attributed with the back and forth movement of the Inter Tropical Convergence Zone (ITCZ) (Lucio et al. 2012). The movement of the ITCZ follows the position of maximum surface heating associated with meridional displacement of the overhead position of the sun, lower latitudes experience higher rainfall and lower temperature, whereas higher latitudes experience lower rainfall and higher temperatures. This creates a large rainfall gradient across latitudes which need to be considered in the simulation. Basin satellite rainfall and temperature series were calculated as the weighted average of all grid boxes by latitudes. For extraction of rainfall, higher latitudes were given lower weights than the lower latitudes while the reverse was applied for temperature.

We computed catchment evapotranspiration from MERRA 2 meter daily air temperature on each catchment with the Hamon model (Oudin et al. 2005). This evapotranspiration model was selected based on a recent finding that very simple evapotranspiration models relying on mean daily temperature are as efficient as more complex models such as the Penman model and its variants (Oudin et al. 2005).

### *6.2.5 Future projections*

Rainfall data from a set of 8 CMIP5 GCMs (Table 6.1) with two emission scenarios was used. The GCMs were downscaled to 0.45° x 0.45° resolution with the SMHI-RCA (Sveriges Meteorologiskaoch Hydrologiska institute) RCM within the CORDEX-Africa regional downscaling experiments. CORDEX is a program sponsored by World Climate Research Program (WCRP) to develop an improved framework for generating regional-scale climate projections for impact assessment and adaptation studies worldwide within the IPCC AR5 timeline and beyond (Giorgi et al. 2009). Climate projection framework within CORDEX is based on the set of new global model simulations planned in support of the IPCC Fifth Assessment Report, referred to as CMIP5 (Taylor et al. 2012). This set of simulations includes a large number of experiments, ranging from new greenhouse-gas scenario simulations for the 21st century, decadal prediction experiments including the carbon cycle and experiments aimed at investigating individual feedback mechanisms (Taylor et al. 2012). These simulations are based on the reference concentration pathways (RCPs), i.e. prescribed greenhouse-gas concentration pathways throughout the 21st century, corresponding to different radiative forcing stabilization levels by the year 2100. Within CMIP5, the highest-priority global model simulations have been selected to be the RCP4.5 and RCP8.5, roughly corresponding to the IPCC SRES emission scenarios B1 and A1B, respectively. The same scenarios are therefore also the highest priority CORDEX simulations (Giorgi et al. 2009). In this study, basin projection data were extracted as described in the observed (section 6.7). Future evapotranspiration was also computed from extracted temperature with the Hamon's model earlier described in section 6.7.

### *6.2.6 Evaluation and Bias Correction of RCM/GCM data*

Bias-adjustment aims at eliminating errors in the climate model data when compared against historic observations (Kling et al. 2012). It rely either on computing the difference between satellite and gauge based precipitation where gauge-based measurements are available or on a combination of several satellite-based estimates in regions with no gauges (Kling et al. 2012). We chose the well known delta-change (Kling et al. 2012) method for bias correction of temperature while quantile mapping (Bürger 2014; Maraun 2014; Maraun 2013) was used for precipitation due to some inadequacies of the delta-change method. The main criticism of the quantile mapping bias correction has been an "Inflation issue" when applied on daily data (Bürger 2014; Maraun 2014; Maraun 2013), this was minimized by conducting the mapping separately for each month. Nevertheless, we compared the original RCM/GCM and bias corrected precipitation data with the observed using six efficiency coefficients displayed in Table 6.2.

## 6.3 Results

### *6.3.1 Hydropower Model Calibration and Validation*

The hydropower model was calibrated (2001-2005) and validated (2006-2010) with the correlation of observed and simulated reservoir level. Good values of 0.56 (NSE), 0.90(d), 0.71 (md), 0.89(r), 0.78(R2) and 0.88(KGE) were recorded during calibration. Similar values of 0.54(NSE), 0.87(d), 0.70 (md), 0.81(r), 0.65(R2) and 0.79(KGE) were observed during hydropower model calibration. This indicates that the model could be used in simulation of climate change impacts on hydropower production in the dam.

### 6.3.2 Projected Trends

### *6.3.3 Climate*

Annual projected rainfall and PET ensemble median from 8 GCMs for upstream the Kainji Lake is displayed in Figure 6.2. In the RCP8.5 scenario, there will be above 100mm increase in ensemble median rainfall upstream the Kainji Lake while under RCP4.5 the upstream area will witness slight increase to mid-century which will be lost at the end of the century. In the RCP8.5 scenario, there will be above 2mm increase in ensemble median PET upstream the Kainji Lake while under RCP4.5 the upstream area will witness about 0.5mm increase which will be stabilized at the mid century.

## Table 6. 1 List of CMIP5 models considered in the study

| Modeling Center (or Group) | Institute ID | Model Name | Resolution |
|---|---|---|---|
| Canadian Centre for Climate Modelling and Analysis | CCCMA | CanESM2 | T63 (;2.8125832.81258) L35 |
| Centre National de Recherches Météorologiques / Centre Européen de Recherche et Formation Avancée en Calcul Scientifique | CNRM-CERFACS | CNRM-CM5 | TL127 (256 3 128) |
| NOAA Geophysical Fluid Dynamics Laboratory | NOAA GFDL | GFDL-ESM2M | M45 (;2832.58) L24 |
| Met Office Hadley Centre (additional HadGEM2-ES realizations contributed by Instituto Nacional de Pesquisas Espaciais) | MOHC | HadGEM2-ES | N96 (;1.24831.8758) L38 |
| Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology | MIROC | MIROC5 | T85 (;1.40625831.406258) L40 |
| Max-Planck-Institut für Meteorologie (Max Planck Institute for Meteorology) | MPI-M | MPI-ESM-LR | T63 (;1.875831.8758) L47 |
| Norwegian Climate Centre | NCC | NorESM1-M | F19 (;1.875832.58) L26 |
| EC-EARTH consortium | EC-EARTH | EC-EARTH | TL159 (320 3 160) |

## Table 6. 2 Efficiency coefficients for model calibration in the Niger basin

| Symbol | Full Name and Range | Reference |
|---|---|---|
| Nash | Nash-Sutcliffe Efficiency ( -Infinity <= Nash <= 1 ) | *Nash and Sutcliffe (1970)* |
| d | Index of Agreement ( 0 <= d <= 1 ) | Legates and McCabe (1999) |
| md | Modified Index of Agreement | *Krause and Boyle (2005)* |
| r | Pearson Correlation coefficient ( -1 <= r <= 1 ) | |
| R2 | Coefficient of Determination ( 0 <= R2 <= 1 ) | *Krause and Boyle (2005)* |
| KGE | Kling-Gupta efficiency ( 0 <= KGE <= 1 ) | *Kling et al. (2012)* |

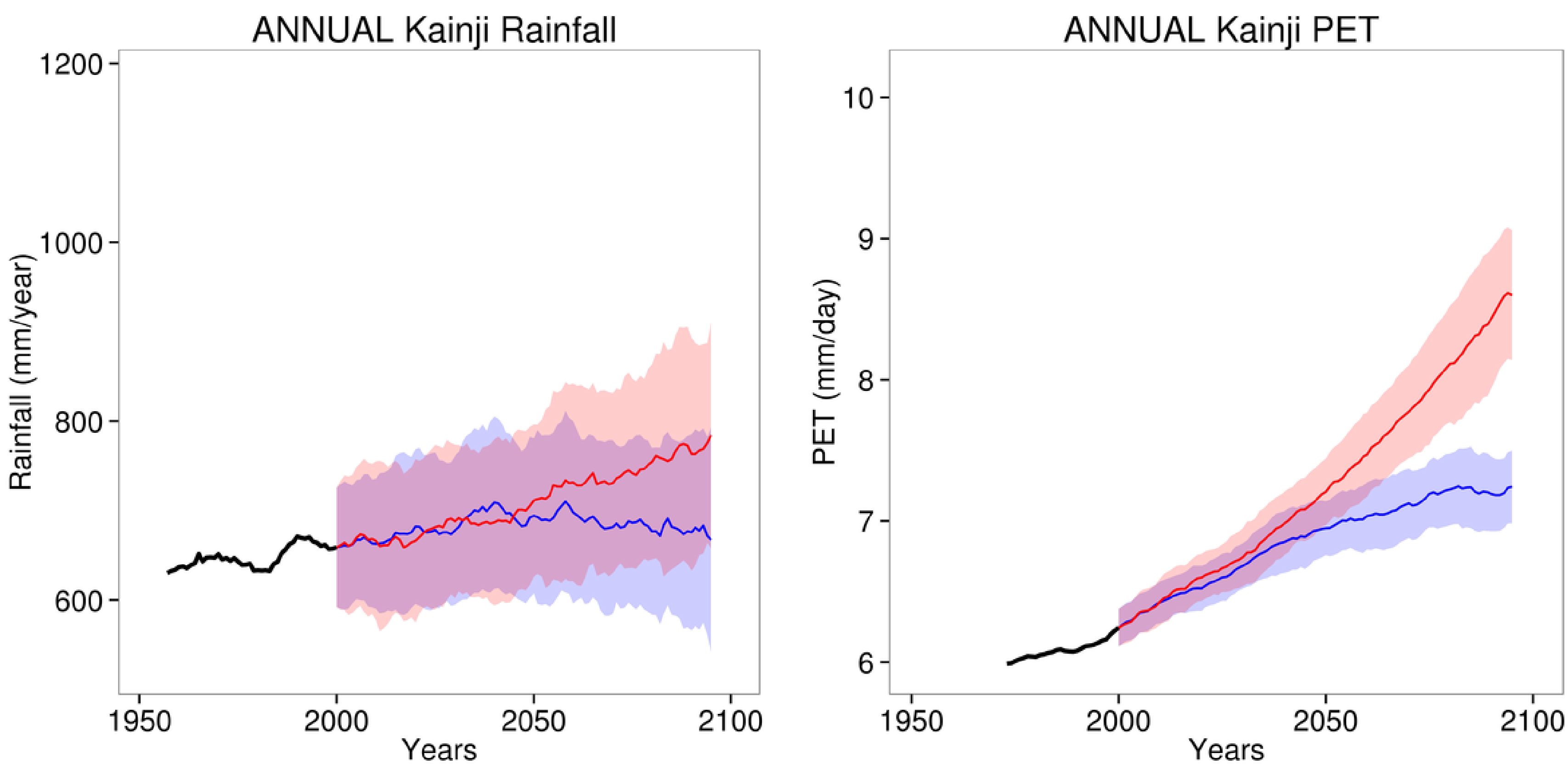



**Fig 6. 2 Projected annual trends of precipitation upstream the Kainji**

### *6.3.4 Hydrological Properties*

Annual projected ensemble median from 8 GCMs impacts of climate change on evaluated hydrological properties (reservoir inflow, controlled release to turbine and reservoir storage) of the Kainji Lake are displayed in Figure 6.3. In the RCP8.5 scenario, there will be more than 500 $m^3/s$ increase in annual average inflow to the Kainji Lake while RCP4.5 will be attributed with about 200 $m^3/s$ increases through mid to the end of the century. For reservoir storage, RCP8.5 scenario will be attributed with about 2.5 $km^3$ increases in annual average storage while RCP4.5 will be attributed with about 1.25 $km^3$ increases through mid to the end of the century. Reservoir level will go through about 1m annual average increase at Kainji under RCP8.5 while a 0.5m increase is expected under RCP4.5 simulations. For the Controlled release to the turbines, about 300 $m^3/s$ increases is expected at the end of the century under RCP8.5 and there will be about 150 $m^3/s$ increase in the RCP4.5 scenario.

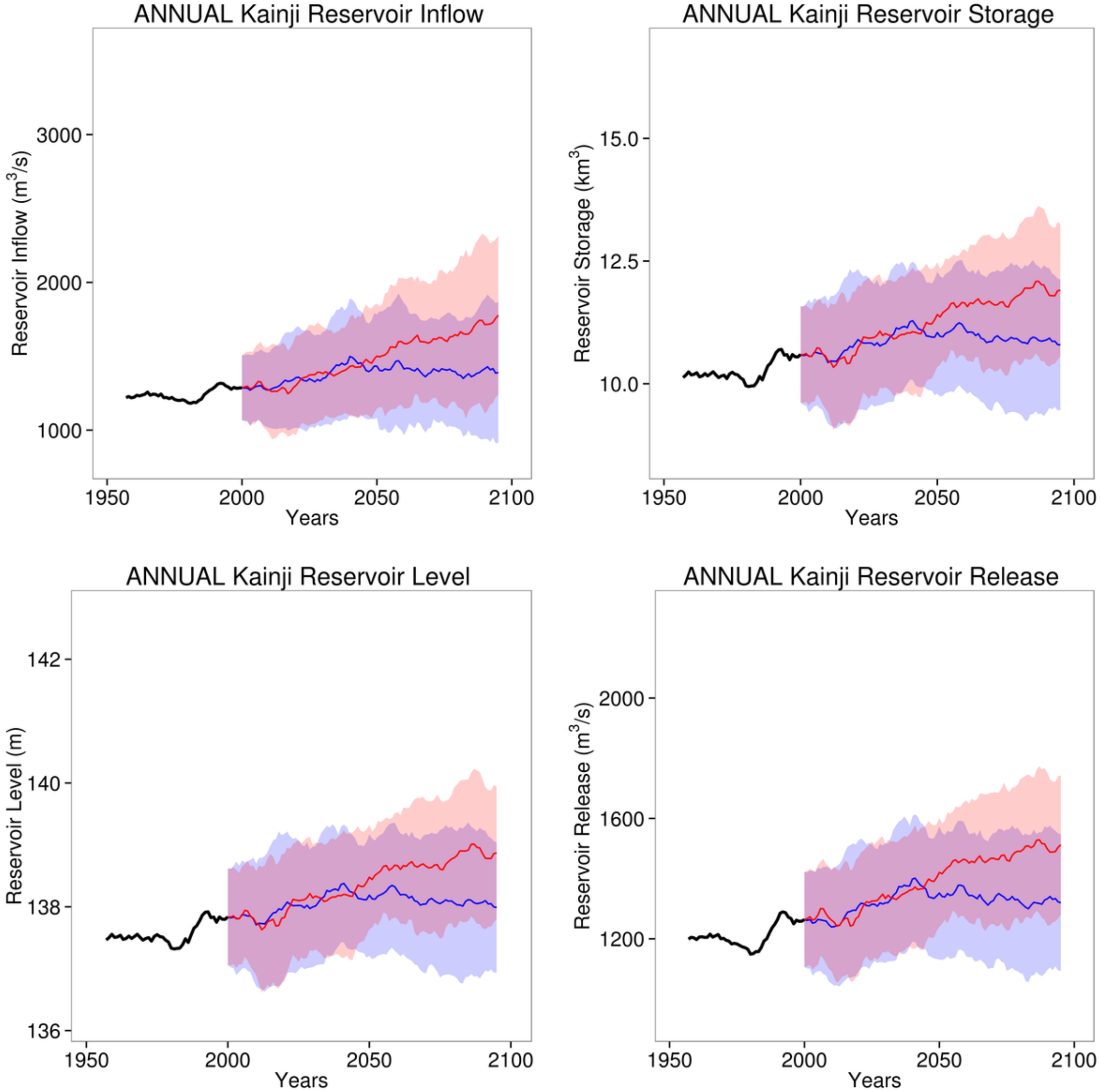



**Fig 6. 3 Projected annual trends of hydrological properties of the Kainji lake**

### *6.3.5 Energy*

Annual projected impacts of climate change on hydropower production in the Kainji dam based on our model simulation from 8 GCMs are displayed in Figure 6.4. Energy production, will experience about 100 MW ensemble median increase is expected at the end of the century under RCP8.5 and there will be about 50 MW increase in the RCP4.5 scenario.

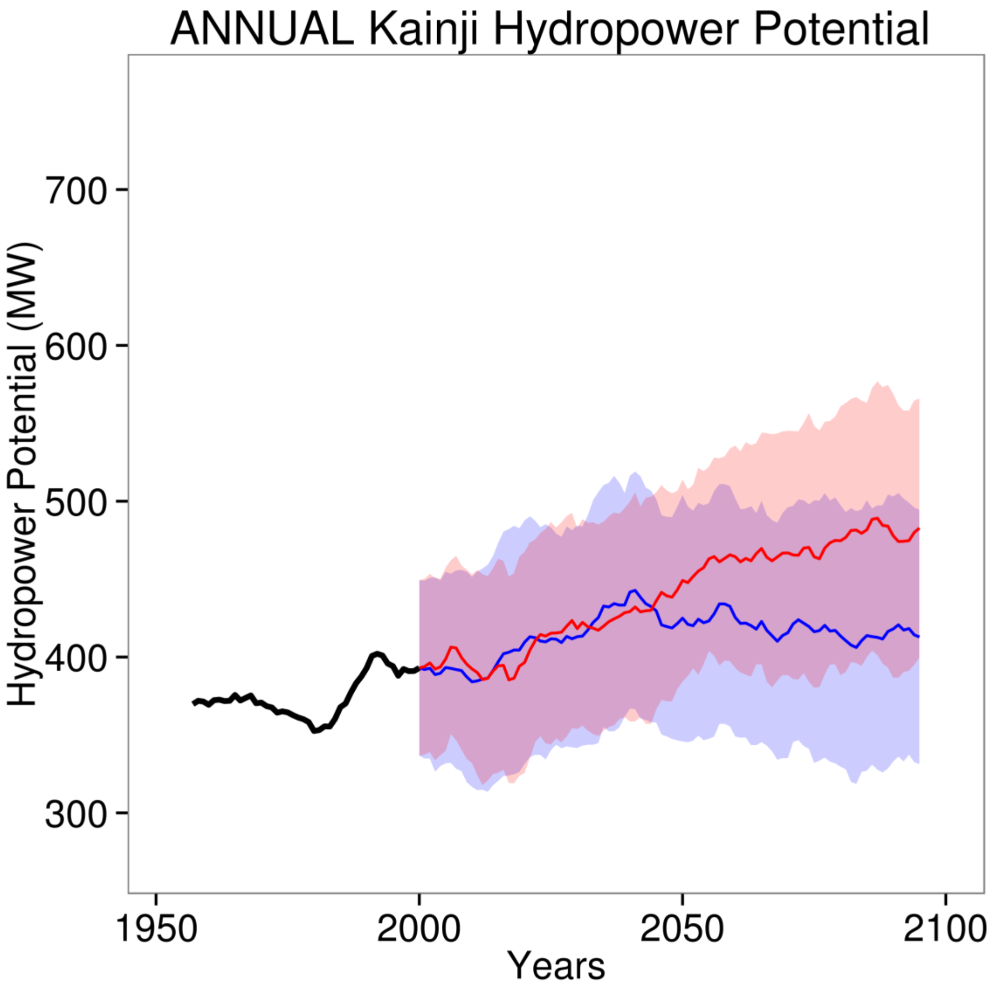



**Fig 6. 4 Projected annual trends of hydropower production in the Kainji lake**

## 6.4 Discussion and Conclusions

Climate change will drive increase in precipitation and PET upstream the Kainji dam. This will be due to large pattern of increase in rainfall in Sahelian region (Chapter 4 and 5) due to intensification of hydrological cycle by increasing atmospheric temperatures, which consequently increases runoff in the evaluated catchments. The study also revealed that the greater the green house gas emissions, the more the hydrological perturbation as observed in the evaluated RCP4.5 and RCP8.5 emission scenarios. Increasing rainfall due to climate change will consequently drive increase in reservoir inflow.

The adopted log-exponential reservoir operations rule in this study was suitable for the Kainji Lake based on the reported efficiency criteria in water level simulation. The same reservoir operations rule was earlier reported to be suitable and easy to fit into different reservoir systems by just adjusting two parameters; and this was confirmed at Kainji (Proussevitch et al. 2013). Rising inflow will drive an increase in the reservoir storage, reservoir level, turbine controlled discharge, and consequently, hydropower production. Hydropower system rely on the potential energy difference between the levels of water in reservoirs, dams or lake and their discharge tail water levels downstream. The water turbines which convert the potential energy of water to shaft rotation are coupled to suitable generators (Rufai et al. 2012).

Projected increase in hydropower potential in the Kainji will add to the untapped African potential for hydropower. Hydropower is by far the most established renewable resource for electricity generation and commercial investment (Rufai et al. 2012). Continuation of the use of fossil fuels is set to face multiple challenges that include: depletion of fossil fuel reserves and other environmental concerns, geopolitical and military conflicts as well as instability in fuel prices (Mohammed et al. 2013). Hydropower systems are easy to run and generally have low maintenance cost compared to other sources of energy. Creation of enabling environment in tapping these huge and clean resources will reduce the worsened electricity shortages in the region and enhance socioeconomic developments (Bartle 2002).

# CHAPTER 7

## Discussion, Summary and Conclusions

In this thesis, the impacts of climate change on local communities and importance of local climate change information in the Niger basin was evaluated (Chapter 3). CMIP5 climate change projections were used to evaluate impacts of climate change on the basin (Chapter 4). A lumped rainfall-runoff model was adapted and used in quantifying the effects of the projected climate change on water resources (Chapter 5). The rainfall-runoff model was then coupled with a developed hydropower model for the Niger basin and was used in evaluating impacts of climate change on hydropower production (Chapter 6). In the remainder of this chapter, the main conclusions from the thesis are drawn in Section 7.6 while some directions for further research are suggested in Section 7.7.

### 7.1 General Conclusions

Empirical observations of the interactions of climate and society and natural systems can be of value in anticipating future impacts. This is commonly achieved through analogue methods, in which variations over space or past time can substitute for future changes. Three kinds of analogue can be identified: historical events, historical trends, and regional or spatial analogues of present climate. A particular advantage of empirical studies emerges as they are extended into the area of adaptation because it becomes possible to ask decision makers, stakeholders, and those impacted directly about how they adapt or have adapted in the past. It is also possible to confirm their responses through direct observations.

Empirical studies can be combined effectively with quantitative model scenarios. Such a combination of approaches permits modeling work to be solidly grounded in experience, and permits the extension of empirical studies into the future. This thesis combined empirical studies effectively with quantitative model scenarios in assessments of impacts of climate change in the Niger basin.

In Chapter 3, we evaluated the consistency of local knowledge and responses to climate change with observations of hydro-climatic variables in the Niger basin. The basin has gone through significant variations in precipitation and river discharge which has different impacts at the local scale. Perceptions of climate indicators were highly consistent with observations demonstrating the value of local knowledge. Local populations gave important information that could improve our understanding of climate trends in data scarce regions. However, impacts of these climatic changes were dependent on environmental factors (such as the location relative to a dam) and how this is captured in local perceptions depends on peoples' memory capability in recalling recent events.

The impacts of climate change on the Niger basin was evaluated in Chapter 4. Results indicated that climate change will drive increase in precipitation with high spatial variability in the Niger basin especially in the high emission scenario RCP 8.5. Close GCM agreement on projected precipitation pattern especially showed great confidence in the CMIP5 projected precipitation pattern across the Niger basin. There was also a consistent decrease in MAM rainfall which could have influence on agriculture. Climate change will also drive an increase in JJA and SON rainfall which will further aggravate the witnessed flooding in the basin due to high intensity of rainfall and population pressure.

In Chapter 5, the improvement of the characteristics of RCM forced by 8 GCMs projected rainfall trends by quantile mapping bias correction revealed the suitability of the adopted method for the region. The improved IHACRES hydrological model used in this study showed high suitability for the basin; based on recorded high calibration and validation efficiency coefficients. Climate change will drive increase in precipitation, temperature, PET and runoff at Kainji and Malanville. This will be due to large pattern of increase in rainfall in Sahelian region (Chapter 4) due to intensification of hydrological cycle by increasing atmospheric temperatures which consequently increases runoff in the evaluated catchments. The study also revealed that the greater the green house gas emissions, the more the hydrological perturbation as observed in the evaluated RCP4.5 and

RCP8.5 emission scenarios. Increases in air temperature could further increase the vulnerability of agriculture through a yield reduction as a result of heat stress, although large discrepancies exist in yield predictions as a result of climate change in the region and the sign of change is uncertain (Roudier et al. 2011). Rise in PET more than precipitation will aggravate the challenges of increased soil moisture drought which is domiciled in the region (IPCC 2014). Close GCM agreements on projected decreasing runoff pattern in the Niger basin showed great confidence in the modeling framework presented in this study.

In Chapter 6, the influence of climate change on hydropower production in the Niger basin was evaluated. Twenty-first century trends of the hydrological properties (reservoir inflow, reservoir storage, reservoir level and controlled turbine release) and hydropower production of the Kainji lake were evaluated. The adopted hydrological model for this study showed high suitability for simulating the reservoir inflow based on recorded high calibration and validation efficiency coefficients. The adopted log-exponential reservoir operations rule in this study was suitable for the Kainji lake based on the reported efficiency criteria in water level simulation. The same reservoir operations rule was earlier reported to be suitable and easy to fit into different reservoir systems by just adjusting two parameters (Proussevitch et al. 2013); and this was confirmed at Kainji.

Rising reservoir inflow will drive an increase in the reservoir storage, reservoir level, turbine controlled discharge, and consequently, hydropower production. Hydropower system rely on the potential energy difference between the levels of water in reservoirs, dams or lake and their discharge tail water levels downstream. The water turbines which convert the potential energy of water to shaft rotation are coupled to suitable generators (Rufai et al. 2012). This implies that greater potential for hydropower production will be experienced in the Kainji lake and the Niger basin. This potential could be positively exploited by expanding the Kainji lake storage capacity, construction of more upstream dams etc, rather than spilling projected excess inflow to the downstream. The spillage of the large fraction of the projected inflow will lead to further destruction on local populations domiciled downstream the dam (Oyerinde et al. 2014).

In addition, projected increase in hydropower potential in the Kainji will add to the untapped African potential for hydropower. Hydropower is by far the most established renewable resource for electricity generation and commercial investment (Rufai et al. 2012). Continuation of the use of fossil fuels is set to face multiple challenges that include: depletion of fossil fuel reserves and other environmental concerns, geopolitical and military conflicts as well as instability in fuel prices (Mohammed et al. 2013). Hydropower systems are easy to run and generally have low maintenance cost compared to other sources of energy. Creation of enabling environment in tapping these huge and clean resources will reduce the worsened electricity shortages in the region and enhance socioeconomic developments (Bartle 2002).

### 7.2 Discussion of significance of local knowledge

Climate change has significant impacts on ecosystems and societies in West Africa and adaptation to it is hindered by poorly documented historical climate trends and future projections. Local communities have responded to variations in water availability through the use of water harvesting, irrigation, planting of drought tolerant and early maturing crop varieties, and others. Therefore, knowledge of local communities on recent climate variability and adaptation measures is very valuable, particularly in the absence of reliable local observations and projections. The IPCC Summary for Policymakers (2014) also showcased that “adaptation planning and implementation at all levels of governance are contingent on societal values, objectives, and risk perceptions”. However, some biases are witnessed in local perceptions, which are caused by some environmental factors such as extreme droughts. Such bias was witnessed in Ethiopia where the perceived 1980s’ dry years due to large-scale famine conditions were one of the wettest years in the region (Meze-Hausken 2004). Kalanda-Joshua et al. (2011) also reported that local perceptions were based on the ability of respondents to recall key events and are thus more accurate on recent climatic events (< 30 years). This thesis attempted to address these challenges by evaluating consistency of local perceptions with recent observations starting from 1990; after recovery from the West African drought was witnessed in some parts of the region (Ali and Lebel 2009). We also assessed the potential of local perceptions in enhancing adaptation efforts in the Niger River Basin (Chapter 3).

## 7.3 General Discussion

All climate change scenarios used in this thesis are based on the fifth phase of the Coupled Model Intercomparison Project (CMIP5) (Taylor et al. 2012). These simulations are based on the reference concentration pathways (RCPs), i.e. prescribed greenhouse-gas concentration pathways throughout the 21st century, corresponding to different radiative forcing stabilization levels by the year 2100. Within CMIP5, the highest-priority global model simulations have been selected to be the RCP4.5 and RCP8.5, roughly corresponding to the IPCC SRES emission scenarios B1 and A1B, respectively (Giorgi et al. 2012). The same scenarios were therefore used in this thesis.

To obtain the actual changes in climate associated with each RCP, climate projections from 8 Global Climate Models (GCMs) were compared. Precipitation, which is the most critical variable for hydrological applications, is a very difficult variable to simulate in climate models. Most climate models, for example, tend to overestimate the amount of “drizzle” (Perkins et al. 2007; Sun et al. 2006). As a result, climate model output typically has a bias compared to observations that should be corrected for (Lenderink et al. 2007).

Several ways exist to do this (Hay et al. 2002; Leander and Buishand 2007; Kling et al. 2012). In Chapter 5, a non-linear correction was applied that corrected the bias, taking into account its spatial and temporal variations(Bürger 2014; Maraun 2014; Maraun 2013). The climate scenarios used in this thesis found to be biased with respect to the observations (Chapter 5). It should be noted that the precipitation and temperature fields are strongly influenced by the bias correction in the sense that the spatial patterns of the model output are “drawn” towards those of the observations. Furthermore, because no information is available for the future, the model bias is generally assumed to be constant in time. Ideally, ensembles of models, both of GCMs and RCMs, should be used, because the multi-model mean is generally a better predictor than individual models (Lambert and Boer 2001). In this thesis, ensembles of the climate predictions were presented along with individual simulations from the different 8 GCMs (Chapters 4, 5 and 6).

The version of IHACRES model adopted and adapted to the Niger basin (Chapter 5) is a lumped parameter, conceptual rainfall-runoff model, based on unit hydrograph (Jakeman et al. 1990). Application of the model is easier because it requires only precipitation and evapotranspiration as input data, and only little computation and calibration time. On the other hand, physical based models require more atmospheric data input and relatively long computation times. Therefore, when assessment of the effects of climate change is the objective, involving simulations over long periods (e.g., hundreds of years), running physically based models at this scale quickly becomes infeasible and one is obliged to use a less complex model. At the scale of large river basins such as the Niger, however, it is not feasible to take into account these hydrological processes in detail, because there is simply too much heterogeneity. At this large scale, conceptual hydrological models often perform as good as or better than complex physically-based hydrological models (te Linde et al. 2007), because the theory that physically-based models are based on is usually only valid at small scales (McDonnell et al. 2007). Simple hydrological models that have often been used to model the water budget in large river basins simplify both subsurface hydrological processes and land-atmosphere interactions, making them relatively fast and easy to operate.

Studies have revealed that very simple evapotranspiration models relying on mean daily temperature are as efficient as more complex models such as the Penman model and its variants (Oudin et al. 2005). In this thesis evapotranspiration input into the hydrological model was computed with the Hamon model (Oudin et al. 2005) which gives great chance of replicating the hydrological simulation in data scarce regions.

In Chapter 5, the efficiency of the adapted IHACRES hydrological model was investigated by comparing simulated streamflow with the observed. As atmospheric forcing for all models, downscaled re-analysis data (i.e., atmospheric model output combined with observations) was used. This dataset was shown to cause relatively poor modeling efficiencies for hydrological models (Gosset and Viarre 2013). Results showed that the adapted IHACRES model presented in this study effectively simulated river discharge in the basin and gives possibility for applications in poorly gauged basins that are rampant in the region.

For several decades, the majority of West African countries have suffered from the electricity shortages, which constitute a serious handicap for their socio- economic development (Gnansounou et al. 2007). The situation has been worsened during the last years due to human activities and climate change. Electricity generation from hydropower makes a substantial contribution to meeting today’s increasing world electricity demands. However, only about 4 per cent of Africa's technically feasible hydro-potential has been developed. Countries in the Niger River basin (West Africa) plan the investment of $200 million in the installation of an additional 400MW of hydropower in the nearest future, adding to the existing 685MW. With the impacts of climate change in the basin already occurring, there is a need for comprehending the influence of future hydro-climatic changes on hydro-power generation in the basin. This study was presented in chapter 6 with a case study of the largest hydropower project (Kainji) in the Niger basin.

The Kainji lake resulted from a multipurpose dam project installed in 1968. The purposes of the reservoir include power generation, progressive development of navigation, flood control in the Niger valley, and estimated fishery production of over 10,000 tons annually. Kainji dam currently supplies 12 % of the total electricity of Nigeria (Mohammed et al. 2013). Optimum performance of the Kainji has been influenced by climate change and other socio-political factors. This thesis evaluated the impacts of $21^{st}$ century climate change on hydrological properties and hydropower production in the Kainji lake. Based on hydrological observations of the dam, we developed a simple hydroelectricity production model to simulate future impacts of climate change on hydropower production in the basin. The hydropower model was coupled with a hydrological model (chapter 6).

Results from the coupled hydropower – hydrological model were evaluated with the observational records of the reservoir and there was good correlation; which implies suitability to the basin.

In this thesis, only effects of climate change were assessed. Under extreme climate, land use effects on streamflow may become significant. Therefore, the next logical step would be to perform a combined analysis. For example, for each climate change scenario, associated land use scenarios could be simulated simultaneously. In order to limit computation time, extremely wet or dry episodes from the climate scenarios could be selected to evaluate the effects of land use changes under extreme conditions. Even better would be to represent vegetation dynamically as is done for example at the global scale in the LPJ (Lund-Potsdam-Jena) model (Biemans et al. 2009). Throughout this thesis, extreme peak flows and low flows were not analyzed. Flood peaks that are relevant for water management, for example the design discharge, could be evaluated in further studies on the basin. To make a statistically reasonable estimate of the design discharge, much longer time series spanning about 10,000 years would be necessary.

In Chapter 6, increasing hydropower potential in the basin was projected by considering mainly climate factors based on emission scenarios. Other socio-political factors such as government policy and insecurity might hamper sustainable development of hydropower production in the basin. Therefore, a critical examination of these subjects will be very important.

# References

Abdulkadir TS, Salami AW, Anwar AR, Kareem AG (2013) Modelling of hydropower reservoir variables for energy generation: neural network approach. Ethiop J Environ Stud Manag Vol 6:310–316.

Ali A, Lebel T (2009) The Sahelian standardized rainfall index revisited. Int J Climatol 29:1705–1714. doi: 10.1002/joc

Amogu O, Descroix L, Yéro KS, Le Breton E, Mamadou I, Ali A, Vischel T, Bader J-C, Moussa IB, Gautier E, Boubkraoui S, Belleudy P (2010) Increasing River Flows in the Sahel? Water 2:170–199. doi: 10.3390/w2020170

Andrews F (2011) ARMAX Transfer Function models. http://hydromad.catchment.org/man/armax.html. Accessed 13 Aug 2015

Andrews FT, Croke BFW, Jakeman AJ (2011) An open software environment for hydrological model assessment and development. Environ Model Softw 26:1171–1185. doi: 10.1016/j.envsoft.2011.04.006

Bartle A (2002) Hydropower potential and development activities. Energy Policy 30:1231–1239.

Ben Mohamed A, Van Duivenbooden N, Abdoussallam S (2002) Impact of Climate Change on Agricultural Production in the Sahel – Part 1. Methodological Approach and Case Study for Millet in Niger. Clim Change

54:327–348. doi: 10.1023/A:1016189605188

Benedict SK, Adeleke OS, Kazuhiro N (2014) Inclusive Growth; An imperative for African Agriculture. http://www.afdb.org/fileadmin/uploads/afdb/Documents/Publications/. Acessed 2014-12-04. 77.

Biasutti M, Giannini A (2006) Robust Sahel drying in response to late 20th century forcings. Geophys Res Lett. doi: 10.1029/2006GL026067

Biemans H, Hutjes RW a., Kabat P, Strengers BJ, Gerten D, Rost S (2009) Effects of Precipitation Uncertainty on Discharge Calculations for Main River Basins. J Hydrometeorol 10:1011–1025. doi: 10.1175/2008JHM1067.1

Bürger G (2014) Comment on “Bias Correction, Quantile Mapping, and Downscaling: Revisiting the Inflation Issue.” J Clim 27:1819–1820. doi: 10.1175/JCLI-D-13-00184.1

Byg A, Salick J (2009a) Local perspectives on a global phenomenon-Climate change in Eastern Tibetan villages. Glob Environ Chang 19:156–166.

Byg A, Salick J (2009b) Local perspectives on a global phenomenon—climate change in Eastern Tibetan villages. Glob Environ Chang 19:156–166. doi: 10.1016/j.gloenvcha.2009.01.010

Carter TR, Parry ML, Harasawa H, Nishioka S (1994) IPCC Technical Guidelines for Assessing Climate Change Impacts and Adaptations. Change 2:1–10.

Chappell A, Agnew CT (2008) How certain is desiccation in west African Sahel rainfall (1930–1990)? J Geophys Res. doi: 10.1029/2007JD009233

Crosson P (1997) Impacts of climate change on agriculture. Clim Issues Br 12.

Cuni-Sanchez A, Fandohan B, Assogbadjo AE, Sinsin B (2012) A countrywide multi-ethnic assessment of local communities' perception of climate change in Benin (West Africa). Clim Dev 4:114–128. doi: 10.1080/17565529.2012.728126

Dai A, Lamb PJ, Trenberth KE, Hulme M, Jones PD, Xie P (2004) The recent Sahel drought is real. Int J Climatol 24:1323–1331. doi: 10.1002/joc.1083

David OO, Salami AW (2012) Assessment of Impact of Hydropower Dams Reservoir Outflow on the Downstream River Flood Regime – Nigeria's Experience, Hydropower - Practice and Application, Dr. Hossein Samadi-Boroujeni (Ed.), ISBN: 978-953-51-0164-2, InTech. http://www.intechopen.com/books/hydropower-practice-and-application/assessment-of-impact-of-hydropower- dams-reservoir-outflow-on-the-downstream-river-flood-regime-niger%0AInTech.

Descroix L, Mahé G, Lebel T, Favreau G, Galle S, Gautier E, Olivry J-C, Albergel J, Amogu O, Cappelaere B (2009) Spatio-temporal variability of hydrological regimes around the boundaries between Sahelian and Sudanian areas of West Africa: A synthesis. J Hydrol 375:90–102. doi: 10.1016/j.jhydrol.2008.12.012

Diallo I, Sylla MB, Giorgi F, Gaye AT, Camara M (2012) Multimodel GCM-RCM Ensemble-Based Projections of Temperature and Precipitation over West Africa for the Early 21st Century. Int J Geophys 2012:1–19. doi: 10.1155/2012/972896

Douville H, Salas-Mélia D, Tyteca S (2006) On the tropical origin of uncertainties in the global land precipitation response to global warming. Clim Dyn 26:367–385. doi: 10.1007/s00382-005-0088-2

Druyan LM (2011) Studies of 21st-century precipitation trends over West Africa. Int J Climatol 31:1415–1424. doi: 10.1002/joc.2180

Dutta D, Welsh W, Vaze J, Kim S, Nicholls D (2011) Improvement in short-term streamflow forecasting using an integrated modelling framework. 19th Int. Congr. Model. Simulation, Perth, Aust. 12–16 December 2011

Falkenmark M (1990) Rapid population growth and water scarcity: the predicament of tomorrows Africa. Popul Dev Rev 81–94.

Fosu-Mensah BY, Vlek PLG, MacCarthy DS (2012) Farmers' perception and adaptation to climate change: A case study of Sekyedumase district in Ghana. Environ Dev Sustain 14:495–505.

Giannini A, Biasutti M, Verstraete MM (2008) A climate model-based review of drought in the Sahel: Desertification, the re-greening and climate change. Glob Planet Change 64:119–128. doi: 10.1016/j.gloplacha.2008.05.004

Giorgi F, Coppola E, Solmon F, Mariotti L, Sylla M, Bi X, Elguindi N, Diro G, Nair V, Giuliani G, Turuncoglu U, Cozzini S, Güttler I, O'Brien T, Tawfik A, Shalaby a, Zakey A, Steiner A, Stordal F, Sloan L, Brankovic C (2012) RegCM4: model description and preliminary tests over multiple CORDEX domains. Clim Res 52:7–29. doi: 10.3354/cr01018

Giorgi F, Jones C, Asrar GR (2009) Addressing climate information needs at the regional level : the CORDEX framework. WMO Bull 58:175–183.

Gnansounou E, Bayem H, Bednyagin D, Dong J (2007) Strategies for regional integration of electricity supply in West Africa. Energy Policy 35:4142–4153. doi: 10.1016/j.enpol.2007.02.023

Gosset M, Viarre J (2013) Evaluation of several rainfall products used for hydrological applications over West Africa using two high-resolution gauge networks. Q Jounal R Meteorol Soc 139:923–940. doi: 10.1002/qj.2130

Green D, Raygorodetsky G (2010) Indigenous knowledge of a changing climate. Clim Change 100:239–242. doi: 10.1007/s10584-010-9804-y

Hay LE, Clark MP, Wilby RL, Gutowski WJ, Leavesley GH, Pan Z, Arritt RW, Takle ES (2002) Use of Regional Climate Model Output for Hydrologic Simulations. J Hydrometeorol 3:571–590. doi: 10.1175/1525-7541(2002)003<0571:UORCMO>2.0.CO;2

Hodgkins GA, Dudley RW, Huntington TG (2003) Changes in the timing of high river flows in New England over the 20th Century. J Hydrol 278:244–252.

Huffman GJ, Adler RF, Arkin P, Chang A, Ferraro R, Gruber A, Janowiak J, Mcnab A, Rudolf B, Schneider U (1997) The Global Precipitation Climatology Project ( GPCP ) Combined Precipitation Dataset. Bull Am Meteorol Soc 78:5–20.

Hulme M (2001) Climatic perspectives on Sahelian desiccation: 1973-1998. Glob Environ Chang 11:19–29.

Huntington TG (2006) Evidence for intensification of the global water cycle: Review and synthesis. J Hydrol 319:83–95. doi: 10.1016/j.jhydrol.2005.07.003

Ibrahim B, Karambiri H, Polcher J, Yacouba H, Ribstein P (2013) Changes in rainfall regime over Burkina Faso under the climate change conditions simulated by 5 regional climate models. Clim Dyn Volume 42:1363–1381. doi: 10.1007/s00382-013-1837-2

Ikusemoran M (2009) Landuse and Landcover Change Detection in the Kainji Lake Basin Nigeria Using Remote Sensing and Gis Approach. Bayero J Pure

Appl Sci 2:83–90.

Institut National de la Statistique et de l'analyse Economique (INSAE) (2013) Resultats provisoires du rgph4. http://www.insae-bj.org/recensement-population.html Acessed 04-03-2015 7.

IPCC (2007) Climate Change 2007 : An Assessment of the Intergovernmental Panel on Climate Change. Change. doi: 10.1256/004316502320517344

IPCC (2014) Summary for policymakers. In: Field CB, Barros VR, Dokken DJ, Mach KJ, Mastrandrea MD, Bilir TE, Chatterjee M, Ebi KL, Estrada YO, Genova RC, Girma B, Kissel ES, Levy AN, MacCracken S, Mastrandrea PR, White LL (eds) Clim. Chang. 2014Impacts, Adapt. Vulnerability. Part A Glob. Sect. Asp. Contrib. Work. Gr. II to Fifth Assess. Rep. Intergov. Panel Clim. Chang. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp 1–32

Jakeman A, Hornberger G (1993) How much complexity is warranted in a rainfall-runoff model? Water Resour Res 29:2637–2649.

Jakeman AJ, Littlewood IG, Whitehead PG (1990) Computation of the instantaneous unit hydrograph and identifiable component flows with application to two small upland catchments. J Hydrol 117:275–300.

Jasiewicz J, Metz M (2011) A new GRASS GIS toolkit for Hortonian analysis of drainage networks. Comput Geosci 37:1162–1173. doi: 10.1016/j.cageo.2011.03.003

Jimoh O (2008) Optimized operation of Kainji Reservoir. J Technol 12:34–42.

Jobard I, Chopin F, Berges JC, Roca R (2011) An intercomparison of 10-day satellite precipitation products during West African monsoon. Int J Remote Sens 32:2353–2376. doi: 10.1080/01431161003698286

Kalanda-Joshua M, Ngongondo C, Chipeta L, Mpembeka F (2011) Integrating indigenous knowledge with conventional science: Enhancing localised climate and weather forecasts in Nessa, Mulanje, Malawi. Phys Chem Earth, Parts A/B/C 36:996–1003. doi: 10.1016/j.pce.2011.08.001

Kemausuor F, Dwamena E, Bart-plange A, Kyei-baffour N (2011) Farmers ' Perception of Climate Change in the Ejura-Sekyedumase District of Ghana. J Agric Biol Sci 6:26–38.

KfW (2010) Adaptation to climate change in the upper and middle Niger. River Basin River Basin snapshot, draft for discussion, Entwicklungsbank, May 2010, p 41.

Kim J, Waliser DE, Mattmann C a., Goodale CE, Hart AF, Zimdars P a., Crichton DJ, Jones C, Nikulin G, Hewitson B, Jack C, Lennard C, Favre A (2013) Evaluation of the CORDEX-Africa multi-RCM hindcast: systematic model errors. Clim Dyn. doi: 10.1007/s00382-013-1751-7

Kling H, Fuchs M, Paulin M (2012) Runoff conditions in the upper Danube basin under an ensemble of climate change scenarios. J Hydrol 424-425:264–277.

Krause P, Boyle D, Bäse F (2005) Comparison of different efficiency criteria for hydrological model assessment. Adv Geosci 5:89–97.

L'Hote Y, Mahe G, Some B, Triboulet JP (2002) Analysis of a Sahelian annual rainfall index from 1896 to 2000; the drought continues. Hydrol Sci J 47:563–572. doi: 10.1080/02626660209492960

Lambert SJ, Boer GJ (2001) CMIP1 evaluation and intercomparison of coupled climate models. Clim Dyn 17:83–106.

Laprise R, Hernández-Díaz L, Tete K, Sushama L, Šeparović L, Martynov A, Winger K, Valin M (2013) Climate projections over CORDEX Africa domain using the fifth-generation Canadian Regional Climate Model (CRCM5). Clim Dyn 41:3219–3246. doi: 10.1007/s00382-012-1651-2

Le Barbé L, Lebel T (1997) Rainfall climatology of the HAPEX-Sahel region during the years 1950-1990. J Hydrol 189:43–73.

Le Barbé L, Lebel T, Tapsoba D (2002) Rainfall variability in West Africa during the years 1950–90. J Clim 187–202.

Leander R, Buishand TA (2007) Resampling of regional climate model output for the simulation of extreme river flows. J Hydrol 332:487–496.

Lebel T, Ali A (2009) Recent trends in the Central and Western Sahel rainfall regime (1990–2007). J Hydrol 375:52–64. doi: 10.1016/j.jhydrol.2008.11.030

Lebel T, Diedhiou A, Henri L (2003) Seasonal cycle and interannual variability of the Sahelian rainfall at hydrological scales. J Geophys Res 108:1–11. doi: 10.1029/2001JD001580

Legates DR, McCabe GJ (1999) Evaluating the use of "goodness-of-fit" measures in hydrologic and hydroclimatic model validation. Water Resour Res 35:233–241.

Legesse D, Vallet-Coulomb C, Gasse F (2003) Hydrological response of a catchment to climate and land use changes in Tropical Africa: Case study south central Ethiopia. J Hydrol 275:67–85.

Lenderink G, Buishand A, van Deursen W (2007) Estimates of future discharges of the river Rhine using two scenario methodologies: direct versus delta approach. Hydrol Earth Syst Sci 11:1145–1159.

Lucio P, Molion L, Valadão C, Conde F, Ramos A, MLD M (2012) Dynamical outlines of the rainfall variability and the ITCZ role over the West Sahel. Atmos Clim Sci 2:337–350.

Mahe, Paturel, Servat, Conway, Dezetter (2005) The impact of land use change on soil water holding capacity and river flow modelling in the Nakambe River, Burkina-Faso. J Hydrol 300:33–43. doi: 10.1016/j.jhydrol.2004.04.028

Maraun D (2014) Reply to “Comment on ‘Bias Correction, Quantile Mapping, and Downscaling: Revisiting the Inflation Issue.’” J Clim 27:1821–1825. doi: 10.1175/JCLI-D-13-00307.1

Maraun D (2013) Bias Correction, Quantile Mapping, and Downscaling: Revisiting the Inflation Issue. J Clim 26:2137–2143. doi: 10.1175/JCLI-D-12-00821.1

Mariotti L, Coppola E, Sylla MB, Giorgi F, Piani C (2011) Regional climate model simulation of projected 21st century climate change over an all-Africa domain: Comparison analysis of nested and driving model results. J Geophys Res 116:D15111. doi: 10.1029/2010JD015068

Mbagwu IGJ, Ladu BMB, Amadi AO (2000) Contributions of the Seasonal and Long Term Flood Patterns of River Niger to the Development and Control of Water Hyacinth ( Eiclthornia Crassipes ) in Kainji Lake , Nigeria. 105–111.

McDonnell JJ, Sivapalan M, Vaché K, Dunn S, Grant G, Haggerty R, Hinz C, Hooper R, Kirchner J, Roderick ML, Selker J, Weiler M (2007) Moving beyond heterogeneity and process complexity: A new vision for watershed hydrology. Water Resour. Res. 43:

Mendelsohn R, Schlesinger ME, Williams L (2000) Comparing impacts across climate models. Integr Assess 1:37–48.

Mertz O, Mbow C, Reenberg A, Diouf A (2009) Farmers' perceptions of climate change and agricultural adaptation strategies in rural Sahel. Environ Manage 804–816. doi: 10.1007/s00267-008-9197-0

Mertz O, Mbow C, Reenberg A, Genesio L, Lambin EF, D'haen S, Zorom M, Rasmussen K, Diallo D, Barbier B, Moussa IB, Diouf A, Nielsen JØ, Sandholt I (2011) Adaptation strategies and climate vulnerability in the Sudano-Sahelian region of West Africa. Atmos Sci Lett 12:104–108. doi: 10.1002/asl.314

Meze-Hausken E (2004) Contrasting climate variability and meteorological drought with perceived drought and climate change in northern Ethiopia. Clim Res 27:19–31.

Mitchell JFB, Johns TC, Gregory JM, Tett SFB (1995) Climate response to increasing levels of greenhouse gases and sulphate aerosols. Nature 376:501–504.

Mkankam Kamga F (2001) Impact of greenhouse gas induced climate change on the runoff of the Upper Benue River (Cameroon). J Hydrol 252:145–156.

Mohammed YS, Mustafa MW, Bashir N, Mokhtar AS (2013) Renewable energy resources for distributed power generation in Nigeria: A review of the potential. Renew Sustain Energy Rev 22:257–268. doi: 10.1016/j.rser.2013.01.020

Mounkaila MS, Abiodun BJ, 'Bayo Omotosho J (2014) Assessing the capability of CORDEX models in simulating onset of rainfall in West Africa. Theor Appl Climatol. doi: 10.1007/s00704-014-1104-4

Nash JE, Sutcliffe JV (1970) River flow forecasting through conceptual models part I — A discussion of principles. J Hydrol 10:282–290. doi: 10.1016/0022-1694(70)90255-6

Negrón Juárez RI, Li W, Fu R, Fernandes K, de Oliveira Cardoso A (2009) Comparison of Precipitation Datasets over the Tropical South American and African Continents. J Hydrometeorol 10:289–299. doi: 10.1175/2008JHM1023.1

Novotny E V., Stefan HG (2007) Stream flow in Minnesota: Indicator of climate change. J Hydrol 334:319–333.

Ogilvie A, Mahéé G, Ward J, Serpantiéé G, Lemoalle J, Morand P, Barbier B, Kaczan D, Lukasiewicz A, Paturel J, Liéénou G, Clanet JC (2010) Water, agriculture and poverty in the Niger River basin. Water Int 35:594–622.

Oguntunde PG, Abiodun BJ (2013) The impact of climate change on the Niger River Basin hydroclimatology , West Africa. Clim Dyn 40:81–94. doi: 10.1007/s00382-012-1498-6

Okeke IN, Abudu AB, Lamikanra A (2001) Microbiological investigation of an outbreak of acute gastroenteritis in Niger State, Nigeria. Clin Microbiol Infect 7:514–516.

Olivry J-C, Chouret A, Gabriel V, Lemoalle J, Bricquet J-P (1996) Hydrologie du lac Tchad. http://www.hydrosciences.fr/sierem/produits/biblio/Hydrologie_lac_tchad.pdf. Accessed 27 Sep 2015

Olomoda IA (2006) Impact of Climatic Change on River Niger Hydrology. 11th Int. Riversymp.

Oudin L, Hervieu F, Michel C, Perrin C, Andréassian V, Anctil F, Loumagne C (2005) Which potential evapotranspiration input for a lumped rainfall–runoff model? J Hydrol 303:290–306. doi: 10.1016/j.jhydrol.2004.08.026

Oyebande L, Odunuga S (2010) Climate change impact on water resources at the transboundary level in West Africa: the cases of the Senegal, Niger and Volta basins. Spec Issue Anal Clim Chang impacts water Resour Dev Econ successes challenges 4:163–172.

Oyerinde G, Wisser D (2014) Multi-Model CIMP5 projected impacts of increased greenhouse gases on the Niger basin and implications for hydropower production. Geophys Res Abstr Vol.16:EGU2014–5926–2.

Oyerinde GT, Hountondji FCC, Wisser D, Diekkruger B, Lawin AE, Odofin AJ, Afouda A (2014) Hydro-climatic changes in the Niger basin and consistency of local perceptions. Reg Environ Chang 14:1–11. doi: 10.1007/s10113-014-0716-7

Ozer P, Erpicum M, Demaree G, Vandiepenbeeck M (2003) DISCUSSION of "Analysis of a Sahelian annual rainfall index from 1896 to 2000; the drought continues" The Sahelian drought may have ended during the 1990s. Hydrol Sci J 48:489–492. doi: 10.1623/hysj.48.3.489.45285

Paeth H, Girmes R, Menz G, Hense A (2006) Improving Seasonal Forecasting in the Low Latitudes. Mon Weather Rev 134:1859–1879. doi: 10.1175/MWR3149.1

Panitz H-J, Dosio A, Büchner M, Lüthi D, Keuler K (2013) COSMO-CLM (CCLM) climate simulations over CORDEX-Africa domain: analysis of the ERA-Interim driven simulations at 0.44° and 0.22° resolution. Clim Dyn 42:3015–30. doi: 10.1007/s00382-013-1834-5

Perkins SE, Pitman AJ, Holbrook NJ, McAneney J (2007) Evaluation of the AR4 climate models' simulated daily maximum temperature, minimum temperature, and precipitation over Australia using probability density functions. J Clim 20:4356–4376.

Proussevitch A, Shiklomanov A, Frolking S, Glidden S, Lammers R, Wisser D (2013) Log-Exponential Reservoir Operating Rules for Global and Regional Hydrological Modeling. http://posters.unh.edu/media/uploads/originals/2013/12/05/2013-12_Fall_AGU.Dams.pdf. Accessed 4 Mar 2015

Pruski FF, Nearing MA (2002) Runoff and soil-loss responses to changes in precipitation: A computer simulation study. J Soil Water Conserv 57:7–16.

Rienecker MM, Suarez MJ, Gelaro R, Todling R, Bacmeister J, Liu E, Bosilovich MG, Schubert SD, Takacs L, Kim G-K, Bloom S, Chen J, Collins D, Conaty A, da Silva A, Gu W, Joiner J, Koster RD, Lucchesi R, Molod A, Owens T, Pawson S, Pegion P, Redder CR, Reichle R, Robertson FR, Ruddick AG, Sienkiewicz M, Woollen J (2011) MERRA: NASA's Modern-Era Retrospective Analysis for Research and Applications. J Clim 24:3624–3648. doi: 10.1175/JCLI-D-11-00015.1

Rodionov S, Overland J (2005) Application of a sequential regime shift detection method to the Bering Sea ecosystem. ICES J Mar Sci 62:328–332. doi:

10.1016/j.icesjms.2005.01.013

Roudier P, Ducharne A, Feyen L (2014) Climate change impacts on river discharge in West Africa: a review. Hydrol Earth Syst Sci Discuss 11:2483–2514. doi: 10.5194/hessd-11-2483-2014

Roudier P, Sultan B, Quirion P, Berg A (2011) The impact of future climate change on West African crop yields: What does the recent literature say? Glob Environ Chang 21:1073–1083. doi: 10.1016/j.gloenvcha.2011.04.007

Rufai IA, Enagi II, Balami AA (2012) Hydropower potential mapping of niger state 1. ASIAN J Nat Appl Sci 1:46–53.

Rummukainen M (2010) State-of-the-art with regional climate models. Wiley Interdiscip Rev Clim Chang 1:82–96. doi: 10.1002/wcc.8

Salami AW, Sule BF (2010) An overview on reservoir operational impact of Kainji, Jebba and Shiroro Dams on the environment. Paper presented at the one day seminar on reservoir operation. Organized by Federal Ministry of Water Resources, Department Dams & Reservoir Operations, pp 1. 1–12.

Sarr B (2012) Present and future climate change in the semi-arid region of West Africa: a crucial input for practical adaptation in agriculture. Atmos Sci Lett 13:108–112. doi: 10.1002/asl.368

Shin M, Guillaume J, Croke B, Jakeman A (2013) Addressing ten questions about conceptual rainfall–runoff models with global sensitivity analyses in R. J Hydrol 503:135–152.

Sillmann J, Kharin V V., Zhang X, Zwiers FW, Bronaugh D (2013) Climate extremes indices in the CMIP5 multimodel ensemble: Part 1. Model evaluation in the present climate. J Geophys Res Atmos 118:1716–1733. doi: 10.1002/jgrd.50203

Sissoko K, Keulen H, Verhagen J, Tekken V, Battaglini A (2010) Agriculture, livelihoods and climate change in the West African Sahel. Reg Environ Chang 11:119–125. doi: 10.1007/s10113-010-0164-y

Sivakumar MVK (1992) Climate Change And Implications For Agriculture In Niger. Clim Change 20:297–312.

Soon W, Baliunas S, Idso C, Idso S, Legates D (2003) Reconstructing Climatic and Environmental Changes of the Past 1000 Years: A Reappraisal. Energy Environ 14:233–296. doi: 10.1260/095830503765184619

Spence A, Poortinga W, Butler C, Pidgeon NF (2011) Perceptions of climate change and willingness to save energy related to flood experience. Nat Clim Chang 1:46–49. doi: 10.1038/nclimate1059

Sulzman EW, Poiani KA, Kittel TGF (1995) Modeling human-induced climatic change: A summary for environmental managers. Environ Manage 19:197–

224.

Sun Y, Solomon S, Dai A, Portmann RW (2006) How often does it rain? J Clim 19:916–934.

Sylla MB, Gaye AT, Jenkins GS, Pal JS, Giorgi F (2010) Consistency of projected drought over the Sahel with changes in the monsoon circulation and extremes in a regional climate model projections. J Geophys Res 115:D16108. doi: 10.1029/2009JD012983

Sylla MB, Giorgi F, Coppola E, Mariotti L (2013) Uncertainties in daily rainfall over Africa: assessment of gridded observation products and evaluation of a regional climate model simulation. Int J Climatol 33:1805–1817. doi: 10.1002/joc.3551

Tambo J, Abdoulaye T (2012) Smallholder farmers' perceptions of and adaptations to climate change in the Nigerian savanna. Reg Environ Chang. doi: 10.1007/s10113-012-0351-0

Taylor KE, Stouffer RJ, Meehl GA (2012) An Overview of CMIP5 and the Experiment Design. Bull Am Meteorol Soc 93:485–498. doi: 10.1175/BAMS-D-11-00094.1

te Linde AH, Aerts JCJH, Hurkmans RTWL, Eberle M (2007) Comparing model performance of two rainfall-runoff models in the Rhine basin using different atmospheric forcing data sets. Hydrol Earth Syst Sci Discuss 4:4325–4360.

Von Storch H, Zorita E, Cubasch U (1993) Downscaling of global climate change estimates to regional scales: an application to Iberian rainfall in wintertime. J Clim 6:1161–1171.

Vörösmarty C, Douglas E (2005) Geospatial indicators of emerging water stress: an application to Africa. Ambio 34:230–236.

West CT, Roncoli C, Ouattara F (2008) Local perceptions and regional climate trends on the Central Plateau of Burkina Faso. L Degrad Dev 19:289–304.

Wigley TML, Jones PD, Briffa KR, Smith G (1990) Obtaining sub-grid-scale information from coarse-resolution general circulation model output. J Geophys Res 95:1943.

Writeshop (2007) Climate Change Adaptation and Water Resource Management in Africa.Synthesis report of WRITESHOP 21-24th February.

Yabi I, Afouda F (2012) Extreme rainfall years in Benin (West Africa). Quat Int 262:39–43. doi: 10.1016/j.quaint.2010.12.010

Ye W, Bates BC, Viney NR, Sivapalan M (1997) Performance of conceptual rainfall-runoff models in low-yielding ephemeral catchments catchments. Water Resour Res 33:153–166.

# APPENDIX

## Appendix I: Questionnaire on Climate Change Impacts on the Niger basin and Adaptation Measures

Dear Sir/Madame,

The West African Science Service Center on Climate Change launched a research Project to study the impacts of Climate Change on Water Resources in affiliation with the University of Abomey Calavi, Repulblic of Benin. The University thereby invite you to spend a little of your time to fill in the following Questionnaire. The responses will be included as part of your contribution to the Doctoral evaluation of the upstream impacts of climate and land use changes on hydrology and functions of the Kanji lake.

**Part I-General background information**

**1.** Date of interview**………………….**

**2.** Start time **……...**End time **………** Time elapsed**……**

**3.** Age of interviewee**……..**Sex**………….**Position in the District**……………**

District **………………** Local Govt**……………..**

**4**. GPS measure (coordinate)

N**………………**E**…..………………**elevation (m)**...….**precision (m)**…….**

**Educational Background**

| | |
|---|---|
| Illiterate | |
| Primary | |
| Secondary | |
| University | |

**5. Respondents' Economic activity on the lake:**

| | |
|---|---|
| Cultivation | |
| Animal Production | |
| Fishing | |
| Energy | |

Others (please specify) ________________________________ **(Transport, Wildlife, etc)**

**6. Local Awareness and Perception of climate variability and trends related to climate change** (over the past 10-20 years)

**6-A- Rainfall:**

| | |
|---|---|
| Important | |
| Unchanged | |
| Little | |

**In historical matrix**

| **Rainfall** | **Now** | **20 years or more** | **Observation** |
|---|---|---|---|
| **Duration (Months)** | | | |
| **Beginning Period** | | | |
| **Distribution** | | | |
| **Length of Dry Season** | | | |

**6-B-Temperature**

| | |
|---|---|
| Warmer | |
| Constant | |
| Colder | |

**In historical Matrix**

| Temperature | Now | 20 years or more | Observation |
|---|---|---|---|
| **Warmer** | | | |
| **Colder** | | | |
| **Length of warmest period** | | | |

**6-C- Flood**

| | |
|---|---|
| Frequent | |
| Important | |
| Constant | |
| Little | |
| | |

Rare

**Period of Great Floods**

| **Flood** | **Now** | **10 years ago** | **20 years ago** | **Observations** |
|---|---|---|---|---|
| **Abundant** | | | | |
| **Constant** | | | | |
| **Little** | | | | |

**6-D- Drought**

Frequent

Rare

Severe

Constant

What are the Consequences of drought in your area?

Crop and Animal loss

Health problems

Water related Conflicts

Others,

Specify……………………………………………………………………………

**6-E- Sedimentation**

High

Constant

Low

**6-E- Turbulent Winds**

| | |
|---|---|
| High | |
| Constant | |
| Low | |

**7 Water Resource Availability**

| | |
|---|---|
| Abundant | |
| Constant | |
| Little | |
| Good | |
| Bad | |

**In historical trend**

| Water Resource | Now | 10 years ago | 20 years ago and beyond | Observations |
|---|---|---|---|---|
| **Abundant** | | | | |
| **Constant** | | | | |
| **Little** | | | | |

**8 Changes in terms of economic production**

| | |
|---|---|
| Increasing | ☐ |
| Unchanged | ☐ |
| Diminishing | ☐ |

**Changes occurring in terms of economy, income-generating activities over time**:

| **Source of Income** | **Now** | **10 years ago** | **20 years ago** | **Observations** |
|---|---|---|---|---|
| **Good** | | | | |
| **Bad** | | | | |
| **Unchanged** | | | | |

**Part II-Soil and Water related issues**

**9.** What are the major problems associated with water resources in your locality?

**……………………………………………………………………………………………**

**……………………………………………………………………………………………**

**……………………………………………………………………………………………**

**…………………………………**

**10.** Does climate influence water resources? Yes/No

What type of influence (in order of vulnerability)?

Reduced Stream flow:

………………………………………………………………………..........

Flood:

………………………………………………………………………................................

..

Soil erosion and Gully formation:

……………………………………………………………

Water quality deterioration:

…………………………………………………………..............

Vegetation decline:

………………………………………………………………………..............

Soil fertility decline:

………………………………………………………………………............

Water stress:

………………………………………………………………………........................

Reduction exploitable area:

…………………………………………………………………...

Others, specify:

………………………………………………………………………….....................

**12.** What soil and water conservation practices are present in your locality and which ones are your preferences?

| | |
|---|---|
| Water Storage | |
| Flood Control | |
| Water Treatment | |
| Agro forestry | |
| Soil amendment | |
| Irrigation | |
| Land Reclamation | |

Others,

Specify……………………………………………………………………………….

**Part V–Climate Change Adaptation**

Is climate variability/change a problem in your area?

| | |
|---|---|
| Yes | |
| No | |

Do you have any means of adaptation? Yes

No

**13.** What are your strategies during drought seasons or in case of production failure?

Irrigation

Diversification (Mixed Farming)

Crop Improvement (use of early maturing varieties)

Water Management (Zai, Mulching,Water harvesting, etc)

Abandoning of land and Migration

Others,

Specify………………………………………………………………………………

…

14 What are your strategies during floods?

Drainage Channels

Dam and Dikes (excess water diversion)

Abandoning of Crop Land and Migration

Diversification (Cultivation of adapted crops).

Others,

Specify……………………………………………………………………………

…

**What are your strategies for ameliorating the effects of Wind**

Wind Breaks

Agro forestry

Boarder trees

Others,

Specify……………………………………………………………………………

…

**What are your strategies for combating water sedimentation?**

Erosion control

River/Lake bank protection

Agro forestry

Others,

Specify……………………………………………………………………………

**14.** Do you receive aid and what type, if any?

………………………………………………………………………………………

………………………………………………………………………………………

………………………………………………………………………………………

**15** What are the major production determinants in your area?

Rainfall

Land Availability (grazing, cropping etc)

Water level/availability

Temperature

Others,

Specify………………………………………………………………………………

…

Do you have access to any weather forecast/report (early warning systems)?

Yes

No

**Part IV - Institutional issues**

**16.** Is any social organisations, NGO and state structure working on climate change and water resources in your area?

Yes

No

**17.** How do you evaluate the efforts made? What's not achieved so far and what could have been done differently?

- ………………………………………………………………………………………………………………

  …………………….
- ………………………………………………………………………………………………………………

  …………………….
- ………………………………………………………………………………………………………………

  …………………….

Is there any collaboration within the Niger Basin?

Yes

No

Are you aware about Integrated Water Resource Management?

Yes

No

Do you Practice any of the methods of IWRM?

Yes ☐

No ☐

**18.** What are the most priority issues in your locality that needs intervention and please forward your suggestion to address it?

- ……………………………………………………………………………… …………………….
- ……………………………………………………………………………… …………………….
- ……………………………………………………………………………… …………………….

**Part VI-Miscellaneous**

**19.** Do you have additional issues to forward pertaining points discussed?

- **……………………………………………………………………………………………………………**
  **……………………….**
- **……………………………………………………………………………………………………………**
  **……………………….**

**20.** Comments of the interviewed person regarding the information provided/Special remarks of the interviewer:

- **……………………………………….**

# Appendix II: Coupled Hydrological and Hydropower model output

```
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[1]
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RCA4_v1_day/Kainji_jd_tas_AFR-44_NOAA-GFDL-GFDL-
ESM2M_historical_r1i1p1_SMHI-RCA4_v1_day_19510101-
20051231_weighted.dat"
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ESM2M_rcp45_r1i1p1_SMHI-RCA4_v1_day_20060101-21001231_weighted.dat"
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RCA4_v1_day/Kainji_jd_Merra_2m_Temp_Daily_weighted.txt"

[1] "rcp45"
[1] "NOAA-GFDL-GFDL-ESM2M"
1997-01-01 1997-01-02 1997-01-03 1997-01-04 1997-01-05 1997-01-06
  22.26712   21.99198   21.62684   21.53334   21.76081   21.44570
1951-01-01 1951-01-02 1951-01-03 1951-01-04 1951-01-05 1951-01-06
  15.47076   15.07020   13.97182   12.87530   12.61983   12.77462
[1] "NOAA-GFDL-GFDL-ESM2M"
[1] "AFR-44"
  1997-01-01   1997-01-02   1997-01-03   1997-01-04   1997-01-05
1997-01-06
```

```
7.841510e-03 2.967909e-02 6.527328e-04 1.121965e-03 5.923471e-05
1.979419e-03
1951-01-01 1951-01-02 1951-01-03 1951-01-04 1951-01-05 1951-01-06
         0          0          0          0          0          0
[1] "allstat is"

        Kainji_NOAA-GFDL-GFDL-ESM2M_AFR-44_BEFORE_clim
ME                                               -0.15
MAE                                               0.46
MSE                                               0.45
RMSE                                              0.67
NRMSE %                                          39.40
PBIAS %                                          -8.80
RSR                                               0.39
rSD                                               0.94
NSE                                               0.84
mNSE                                              0.68
rNSE                                              0.52
d                                                 0.96
md                                                0.84
rd                                                0.87
cp                                               -0.86
r                                                 0.92
R2                                                0.85
bR2                                               0.76
KGE                                               0.87
VE                                                0.74
        Kainji_NOAA-GFDL-GFDL-ESM2M_AFR-44_BIAS_CORRECTED_clim
ME                                                       0.10
MAE                                                      0.38
MSE                                                      0.32
RMSE                                                     0.57
NRMSE %                                                 33.40
PBIAS %                                                  5.50
RSR                                                      0.33
rSD                                                      1.00
NSE                                                      0.89
mNSE                                                     0.74
rNSE                                                    -3.96
d                                                        0.97
md                                                       0.87
rd                                                      -0.27
cp                                                      -0.34
r                                                        0.95
R2                                                       0.89
bR2                                                      0.89
KGE                                                      0.92
VE                                                       0.79
        Kainji_NOAA-GFDL-GFDL-ESM2M_AFR-44_BEFORE_monthly
ME                                                  -4.69
```

| | |
|---|---|
| MAE | 18.48 |
| MSE | 689.86 |
| RMSE | 26.27 |
| NRMSE % | 51.10 |
| PBIAS % | -8.80 |
| RSR | 0.51 |
| rSD | 1.01 |
| NSE | 0.74 |
| mNSE | 0.58 |
| rNSE | 0.29 |
| d | 0.93 |
| md | 0.80 |
| rd | 0.82 |
| cp | 0.36 |
| r | 0.87 |
| R2 | 0.76 |
| bR2 | 0.69 |
| KGE | 0.85 |
| VE | 0.65 |

| | Kainji_NOAA-GFDL-GFDL-ESM2M_AFR-44_BIAS_CORRECTED_monthly |
|---|---|
| ME | 2.96 |
| MAE | 17.61 |
| MSE | 678.25 |
| RMSE | 26.04 |
| NRMSE % | 50.70 |
| PBIAS % | 5.50 |
| RSR | 0.51 |
| rSD | 1.08 |
| NSE | 0.74 |
| mNSE | 0.60 |
| rNSE | -5.93 |
| d | 0.94 |
| md | 0.81 |
| rd | -0.68 |
| cp | 0.37 |
| r | 0.88 |
| R2 | 0.78 |
| bR2 | 0.78 |
| KGE | 0.85 |
| VE | 0.67 |

| | Kainji_NOAA-GFDL-GFDL-ESM2M_AFR-44_BEFORE_Seasonal |
|---|---|
| ME | -13.82 |
| MAE | 34.11 |
| MSE | 1964.75 |
| RMSE | 44.33 |
| NRMSE % | 34.10 |
| PBIAS % | -8.80 |
| RSR | 0.34 |
| rSD | 0.97 |

| | |
|---|---|
| NSE | 0.88 |
| mNSE | 0.68 |
| rNSE | 0.52 |
| d | 0.97 |
| md | 0.84 |
| rd | 0.87 |
| cp | 0.94 |
| r | 0.95 |
| R2 | 0.89 |
| bR2 | 0.82 |
| KGE | 0.89 |
| VE | 0.78 |

| | Kainji_NOAA-GFDL-GFDL-ESM2M_AFR-44_BIAS_CORRECTED_Seasonal |
|---|---|
| ME | 8.74 |
| MAE | 30.78 |
| MSE | 1896.30 |
| RMSE | 43.55 |
| NRMSE % | 33.50 |
| PBIAS % | 5.50 |
| RSR | 0.34 |
| rSD | 1.03 |
| NSE | 0.89 |
| mNSE | 0.71 |
| rNSE | -0.46 |
| d | 0.97 |
| md | 0.86 |
| rd | 0.64 |
| cp | 0.94 |
| r | 0.95 |
| R2 | 0.90 |
| bR2 | 0.88 |
| KGE | 0.92 |
| VE | 0.80 |

| | BIAS CORRECTED | GPCP | BEFORE |
|---|---|---|---|
| 1997-01-01 | 479.8275 | 610.6659 | 407.5125 |
| 1998-01-01 | 605.8197 | 637.3806 | 527.9132 |
| 1999-01-01 | 738.4914 | 674.8878 | 649.1972 |
| 2000-01-01 | 820.0333 | 597.6710 | 702.0720 |
| 2001-01-01 | 699.1048 | 629.2193 | 622.7556 |
| 2002-01-01 | 730.0744 | 586.0058 | 605.7467 |
| 2003-01-01 | 695.0521 | 701.2207 | 603.2430 |
| 2004-01-01 | 578.3159 | 627.9121 | 507.7520 |
| 2005-01-01 | 642.2584 | 629.4816 | 569.5154 |
| 2006-01-01 | 736.6358 | 661.3367 | 623.8730 |
| 2007-01-01 | 651.7579 | 651.0380 | 554.1591 |
| 2008-01-01 | 670.8394 | 682.5111 | 580.7529 |
| 2009-01-01 | 711.2988 | 631.2669 | 635.7335 |
| 2010-01-01 | 726.8511 | 667.8146 | 610.6064 |
| 1951-01-01 | | | |

```
[1] "GOF CAL is"
        Kainji_rcp45_NOAA-GFDL-GFDL-ESM2M_CAL
ME                                     -17.75
MAE                                    347.40
MSE                                 184961.88
RMSE                                   430.07
NRMSE %                                 50.30
PBIAS %                                 -1.50
RSR                                      0.50
rSD                                      0.86
NSE                                      0.75
mNSE                                     0.54
rNSE                                     -Inf
d                                        0.92
md                                       0.75
rd                                       -Inf
cp                                    -192.25
r                                        0.86
R2                                       0.75
bR2                                      0.68
KGE                                      0.81
VE                                       0.71
[1] "GOF ALL is"
        Kainji_rcp45_NOAA-GFDL-GFDL-ESM2M_ALL
ME                                     -17.75
MAE                                    347.40
MSE                                 184961.88
RMSE                                   430.07
NRMSE %                                 50.30
PBIAS %                                 -1.50
RSR                                      0.50
rSD                                      0.86
NSE                                      0.75
mNSE                                     0.54
rNSE                                     -Inf
d                                        0.92
md                                       0.75
rd                                       -Inf
cp                                    -192.25
r                                        0.86
R2                                       0.75
bR2                                      0.68
KGE                                      0.81
VE                                       0.71

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5388.876
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5670.667
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4568.773
[25] 4703.116 5111.594 5759.039 4831.854 5256.549 4704.716 4921.895
5604.047
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3 3 3 3

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352.8128
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838.1295
[3,] 1346.2775  988.0728293  692.06993  461.9445 502.6118  814.7417
1112.9410
[4,] 1744.8897 1316.9940786  938.74253  660.4457 630.0129 1047.3356
1587.1619
[5,] 2786.0509 2121.0588654 1495.74648 1084.2417 863.4260 1683.8261
2662.7972
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[1,]  708.5338 1103.797 1003.610  806.259  586.108
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[3,] 1755.6109 2453.835 2630.107 2278.553 1805.554
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1631.302
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1879.919
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"Dec"

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[,7]
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393.3389
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866.9867
[3,] 1159.8533200  852.85791  593.46801 408.3758 466.8196  756.8255
1111.7725
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```
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1456.3633
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1836.4394
          [,8]     [,9]    [,10]    [,11]    [,12]
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$n
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$conf
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[,8]
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1562.998
[2,] 1353.027 995.2497 697.1303 481.7481 524.0446 866.1864 1281.7883
1948.661
         [,9]    [,10]    [,11]   [,12]
[1,] 2063.378 2081.872 1742.740 1359.68
[2,] 2596.204 2716.798 2305.388 1820.75

$out
 [1] 2776.878 2080.630 1495.747 1084.242 4351.652 5061.477 4964.396
4454.450
 [9] 4237.406 3597.990 3406.957

$group
 [1]  1  2  3  4  9 10 10 11 11 12 12

$names
 [1] "Jan" "Feb" "Mar" "Apr" "May" "Jun" "Jul" "Aug" "Sep" "Oct" "Nov"
"Dec"

$stats
             [,1]         [,2]        [,3]      [,4]     [,5]
[,6]
[1,]    0.1138006    0.4887506    5.472163   27.9359 243.8984
353.5382
[2,]  989.4843637  710.1549954  500.971176  358.5289 419.4107
663.2628
[3,] 1388.3374752 1015.3199675  705.303864  432.7012 519.2465
828.4840
[4,] 2131.1528732 1571.0983197 1103.110966  749.0741 660.1157
1072.7156
[5,] 3356.5091820 2505.1603066 1783.485636 1175.7483 969.9309
1635.0486
```

```
          [,7]      [,8]     [,9]    [,10]    [,11]    [,12]
[1,]  498.7074  708.5338 1380.052 1555.036 1336.688 1056.387
[2,]  831.6751 1548.2020 2136.160 2133.724 1758.001 1334.844
[3,] 1195.1356 1873.2422 2792.854 2962.659 2463.744 1931.159
[4,] 2045.5505 2903.7063 3800.790 4029.327 3445.679 2782.665
[5,] 3371.5205 4748.4594 4992.029 5854.442 5391.814 4360.952

$n
 [1] 30 30 30 30 30 30 30 30 30 30 30 30

$conf
         [,1]     [,2]     [,3]     [,4]    [,5]     [,6]      [,7]
[,8]
[1,] 1059.004  766.966 531.6063 320.0417 449.811 710.3703  844.9724
1482.224
[2,] 1717.671 1263.674 879.0015 545.3606 588.682 946.5977 1545.2989
2264.261
         [,9]    [,10]    [,11]    [,12]
[1,] 2312.663 2415.840 1976.904 1513.510
[2,] 3273.046 3509.479 2950.584 2348.808

$out
 [1] 5388.876 4032.365 2897.628 1922.193 1025.833 1224.670 1692.009
5470.079
 [9] 9012.804 6323.095 9964.931 8655.009 6989.089

$group
 [1]  1  2  3  4  5  5  6  8  9  9 10 11 12

$names
 [1] "Jan" "Feb" "Mar" "Apr" "May" "Jun" "Jul" "Aug" "Sep" "Oct" "Nov"
"Dec"

$stats
             [,1]        [,2]        [,3]       [,4]     [,5]
[,6]
[1,]    0.1137183    1.056825    5.041729   37.90523 199.8535
360.4272
[2,]  972.1593089  708.348360  480.957793  324.99345 386.4659
685.7722
[3,] 1270.3467449  918.965267  629.356173  417.58659 546.8411
977.4001
[4,] 1985.0408609 1492.485145 1042.044322  713.58948 644.0335
1356.7715
[5,] 2953.4174102 2250.487248 1641.188589 1140.64972 979.6290
1949.8647
          [,7]      [,8]     [,9]    [,10]    [,11]     [,12]
[1,]  473.6612  823.9519 1173.162 1257.449 1045.665  816.3987
[2,]  917.5152 1182.0116 1854.484 1997.580 1722.183 1341.8936
[3,] 1305.9986 1629.0383 2353.172 2622.364 2187.092 1727.4128
```

```
[4,] 1985.9461 2594.6141 3283.146 3785.332 3272.793 2591.7769
[5,] 2902.8053 4568.7726 5111.594 5604.047 4736.381 3780.7568

$n
 [1] 30 30 30 30 30 30 30 30 30 30 30 30

$conf
          [,1]      [,2]     [,3]     [,4]     [,5]      [,6]
[,7]
[1,]  978.1636  692.7675 467.5011 305.4894 472.5413  783.8388
997.7913
[2,] 1562.5299 1145.1630 791.2112 529.6838 621.1410 1170.9614
1614.2059
         [,8]     [,9]    [,10]    [,11]    [,12]
[1,] 1221.549 1941.050 2106.657 1739.792 1366.862
[2,] 2036.528 2765.294 3138.072 2634.393 2087.963

$out
[1] 5759.039

$group
[1] 9

$names
 [1] "Jan" "Feb" "Mar" "Apr" "May" "Jun" "Jul" "Aug" "Sep" "Oct" "Nov"
"Dec"

[1] "P"           "E"           "simAll_cord"
     Index                  P                 E            simAll_cord
 Min.   :1951-01-01   Min.   : 0.0000   Min.   : 1.870   Min.   :
0.002
 1st Qu.:1988-07-01   1st Qu.: 0.1205   1st Qu.: 3.868   1st Qu.:
705.141
 Median :2025-12-31   Median : 0.9982   Median : 6.628   Median :
1277.307
 Mean   :2025-12-31   Mean   : 1.9591   Mean   : 6.575   Mean   :
1550.032
 3rd Qu.:2063-07-01   3rd Qu.: 3.2262   3rd Qu.: 8.945   3rd Qu.:
2113.402
 Max.   :2100-12-31   Max.   :25.6373   Max.   :14.115   Max.
:10137.830
                                                         NA's   :2
$nstations
[1] 8

$ntimestamps
[1] 54422

$begin
[1] "1952-01-01 01:00:00 WAT"
```

```
$end
[1] "2100-12-31 01:00:00 WAT"

$beginStationSeries
                        P                         E
simAll_cord
"1952-01-01 01:00:00 WAT" "1952-01-01 01:00:00 WAT" "1952-01-01
01:00:00 WAT"
                fut_level                   fut_vol
fut_rel
"1952-01-01 01:00:00 WAT" "1952-01-01 01:00:00 WAT" "1952-01-01
01:00:00 WAT"
               fut_energy                  spillage
"1952-01-01 01:00:00 WAT" "1952-01-01 01:00:00 WAT"

$endStationSeries
                        P                         E
simAll_cord
"2100-12-31 01:00:00 WAT" "2100-12-31 01:00:00 WAT" "2100-12-31
01:00:00 WAT"
                fut_level                   fut_vol
fut_rel
"2100-12-31 01:00:00 WAT" "2100-12-31 01:00:00 WAT" "2100-12-31
01:00:00 WAT"
               fut_energy                  spillage
"2100-12-31 01:00:00 WAT" "2100-12-31 01:00:00 WAT"

$summary
             P      E simAll_cord fut_level fut_vol fut_rel
fut_energy
Min.     0.0000  1.870       44.14      -999    -999    -999       -
999
1st Qu.  0.1205  3.870      707.00      -999    -999    -999       -
999
Median   0.9947  6.637     1279.00      -999    -999    -999       -
999
Mean     1.9590  6.579     1554.00      -999    -999    -999       -
999
3rd Qu.  3.2270  8.951     2115.00      -999    -999    -999       -
999
Max.    25.6400 14.120    10140.00      -999    -999    -999       -
999
        spillage
Min.        -999
1st Qu.     -999
Median      -999
Mean        -999
3rd Qu.     -999
Max.        -999
```

```
[1] "rcp45"
[1] "NOAA-GFDL-GFDL-ESM2M"
$nstations
[1] 8

$ntimestamps
[1] 54422

$begin
[1] "1952-01-01 01:00:00 WAT"

$end
[1] "2100-12-31 01:00:00 WAT"

$beginStationSeries
                        P                          E
simAll_cord
"1952-01-01 01:00:00 WAT" "1952-01-01 01:00:00 WAT" "1952-01-01
01:00:00 WAT"
                fut_level                    fut_vol
fut_rel
"1952-01-01 01:00:00 WAT" "1952-01-01 01:00:00 WAT" "1952-01-01
01:00:00 WAT"
               fut_energy                   spillage
"1952-01-01 01:00:00 WAT" "1952-01-01 01:00:00 WAT"

$endStationSeries
                        P                          E
simAll_cord
"2100-12-31 01:00:00 WAT" "2100-12-31 01:00:00 WAT" "2100-12-31
01:00:00 WAT"
                fut_level                    fut_vol
fut_rel
"2100-12-31 01:00:00 WAT" "2100-12-31 01:00:00 WAT" "2100-12-31
01:00:00 WAT"
               fut_energy                   spillage
"2100-12-31 01:00:00 WAT" "2100-12-31 01:00:00 WAT"

$summary
              P      E simAll_cord fut_level   fut_vol fut_rel
fut_energy
Min.     0.0000  1.870       44.14     131.2 2.411e+09   479.5
121300000
1st Qu.  0.1205  3.870      707.00     136.7 9.153e+09   969.8
287300000
Median   0.9947  6.637     1279.00     138.7 1.172e+10  1114.0
347800000
Mean     1.9590  6.579     1554.00     138.4 1.133e+10  1388.0
438400000
```

```
3rd Qu.  3.2270  8.951     2115.00     140.3 1.366e+10  1971.0
638700000
Max.    25.6400 14.120    10140.00     141.3 1.500e+10  2250.0
747500000
         spillage
Min.            0
1st Qu.         0
Median          0
Mean     14290000
3rd Qu.         0
Max.    681500000
```

# List of Publication and Presentations

## First-author peer-reviewed article:

**Oyerinde, G.T.,** Hountondji, F.C.C., Wisser, D., Diekkrüger, B., Lawin, A.E., Odofin, A.J., Afouda, A., 2014. Hydro-climatic changes in the Niger basin and consistency of local perceptions. Reg. Environ. Chang. 15, 1627–1637. doi:10.1007/s10113-014-0716-7

## Oral Presentations

**Ganiyu Oyerinde** and Dominik Wisser, 2014. 'Multi-Model CIMP5 projected impacts of increased greenhouse gases on the Niger basin and implications for hydropower production'. Presented at the European Geophysical Union General Assembly, Austria, 27th April – 2nd May, 2014. Geophysical Research Abstracts, Vol. 16, EGU2014-5926-2, 2014.

**Ganiyu Titilope Oyerinde,** Hountondji F.C.C., Wisser D., Diekkrüger B., Lawin E.A., Afouda A., Odofin A. J., and Adegbidi A.A**.,** 2013. 'Amelioration of Climate Change Uncertainties with Indigenous Knowledge in the Niger Basin, West Africa' presented at Interdisciplinary Conference of Young Earth System Scientists (ICYESS2013), Hamburg, Germany, 22 – 25 September 2013.

**Oyerinde G. T.**, 2013. ‘Perceptions and Observations of Climate Change in the Niger Basin’ presented at the Board meeting of the Centre for Development Research (ZEF), University of Bonn, Germany, September 19, 2013.