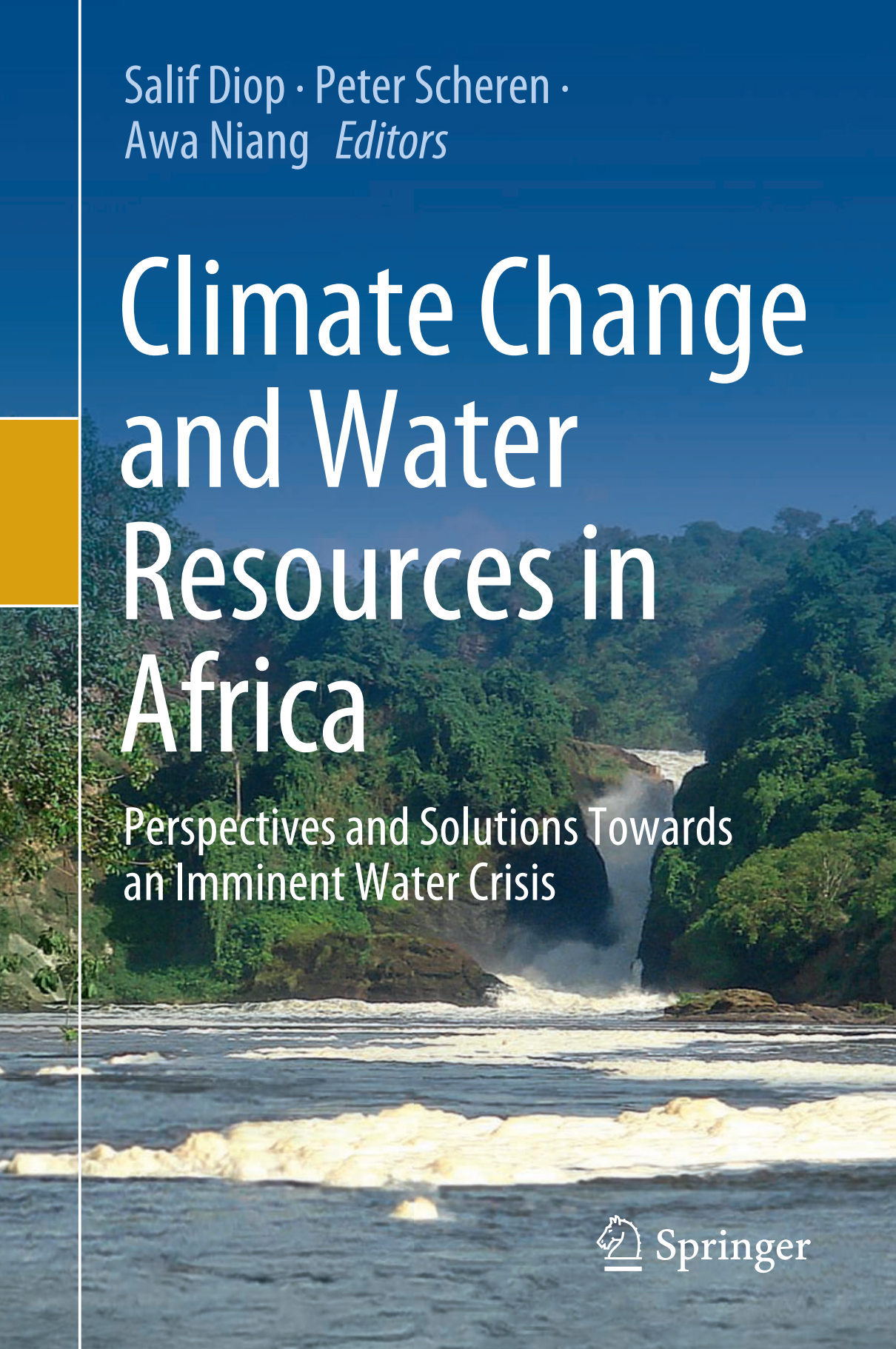
Salif Diop · Peter Scheren · Awa Niang *Editors*

Climate Change and Water Resources in Africa

Perspectives and Solutions Towards an Imminent Water Crisis



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Perspectives and Solutions Towards an Imminent Water Crisis

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This book is dedicated to Nelson Rolihlahla Mandela "Madiba" (1918–2013), the first post-apartheid President of South Africa. He said, "put your thoughts in order by reflection, pen in hand. Appropriate yourself the power of the pen. Read, read, read every day, pen in hand."

Foreword by Felix D. Dakora

The warming rate of Africa over the last 27 years is the most alarming signal of the need for urgent action to mitigate its effects and implement strategies for climate resilience. Based on the fourth and fifth reports of the International Panel on Climate Change (IPCC), it is predicted that average temperatures in Africa will have increased between 2 and 4°C before the end of this century. At the same time, a decrease in rainfall of up to 20% as well as extreme events such as floods and droughts may eliminate considerable portions of low-lying lands, particularly affecting small island states.

There are many implications of climatic variability and change in Africa; one of the most key ones is the impact on water resources and hydrological systems, which directly affect water availability and, in turn, water security as a whole. These effects will negatively impact water provisioning, as well as rain-fed agricultural productivity in many parts of Africa, with variation in impacts occurring in specific places and localities. Various other changes and modifications are likely to occur in response to the significant variability in the global climate system, including extreme aridity in some cases and flooding in others. It is clear, therefore, that integrating climate change risks and opportunities into development decision-making is both a challenge and a necessity facing the African continent, particularly for the most vulnerable countries.

This book, *Climate Change and Water Resources in Africa*, sets out the many challenges and implications of climate change for freshwater resources in Africa, including its rivers, lakes, and aquifers. Under the influence of a range of human factors, the status of water resources in Africa has been changing for decades, playing out in disruption of water flow and variability, falling groundwater levels, changes in rainfall levels, and timing, and an overall decrease in water quality. Indeed, change is not new in this context. Climate change, however, will strongly accelerate the rate of change, affecting the ability of people and societies to respond in a timely manner to address their own needs.

This ability to respond to change is compounded by uncertainty relating to the impacts of climate change. While there are a number of models that attempt to predict these impacts, many are on a generalized scale and do not project localized impacts. Also, the models themselves operate with a high level of uncertainty

and often predict contradictory outcomes, depending upon the model. Thus, African governments must manage these changes in the context of significant uncertainty. This requires adaptive management, encompassing continuous improvement underpinned by rigorous science, in order to understand the drivers of change over time and to be able to address them effectively.

With this in mind, the goal of this book is to offer a deeper analysis of the effects of climate on water resources in some of the most vulnerable areas in Africa, including approaches that may help reduce or mitigate the impacts of climate change. In this regard, while there is no quick fix to the pressures imposed on water resources by climate change, it is clear that increasing the resilience of ecosystems and communities to extreme events such as flooding and drought and integrating climate change risks and opportunities into development decision-making, will be key. It is also important that the wealthier countries assume responsibility for their historic greenhouse gas (GHG) emissions and support those countries that are most impacted by those emissions by contributing to their adaptations to climate change while reducing their own carbon footprints. Wealthy countries and those countries that are now major contributors to GHG emissions must make major and long-term contributions to development, technology transfer, training, and capacity building, notably in Africa. As a whole, this book intends to contribute to the debate around climate change in relation to water resource management on the African continent, and in particular, inform policy decisions and actions that will improve the ability of governments and communities to manage the challenges of climate change and variability in relation to the aquatic ecosystems upon which they depend.

Close collaboration among the editors, Prof. Salif Diop, Dr. Peter Scheren, and Dr. Awa Niang, has been the driving force behind, "Climate Change and Water Resource Management in Africa." The editors would also like to thank the authors who contributed their time and expertise to this important resource. It is our hope and belief that this book will provide important, actionable information to the public at large, and specifically to the many dedicated scientists, researchers, managers, decision-makers, and policymakers that are working together to safeguard, protect, and sustainably manage water resources in a changing climate in Africa.

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Foreword by Daniel Nyanganyura

Recognizing the critical role of water in supporting human livelihood, economic growth and the very survival of the population, African governments developed the Africa Water Vision, describing an Africa that exhibits equitable and sustainable use and management of water resources for poverty alleviation, socioeconomic development, regional cooperation, and the environment. However, it is clear that this vision will become reality only when a range of challenges is properly addressed[1]. Moreover, the increasingly visible effects of climate change on water resources in Africa are compounding the challenge.

Consistent with global warming patterns, Africa is already experiencing significant spatial and temporal rainfall variability, with resulting challenges in terms of sustainable management of freshwater resources (Africa Water Vision for 2025, UNECA).

Large rural and semi-arid regions of the Sahel, central and eastern Southern Africa, and the Horn of Africa are at particular risk because they depend largely on rainfed agriculture. Increased climate variability, including more intense droughts and floods, increases temperatures, and reduces rainfall in these regions, putting these communities at significant risk. In particular, there is a need to protect the critical 'water towers' of central, west, and eastern Africa, (e.g., Congo forests; west Africa Fouta Djallon mountain areas; Eastern Africa and Ethiopian highlands), as deforestation and poor land-use management in these places have significantly decreased their effectiveness as critical catchment areas. Their protection and restoration are therefore critically important in order to secure continuous provisioning functions.

Recognizing the many weaknesses across the continent that complicate effective responses to climate change (e.g., limited institutional capacity, the scale of poverty, data scarcity, poor reliability of climate change models at local scale), immediate action is needed to improve community and societal resilience to climate change. Key approaches for good water management include alignment of water management plans with national development and poverty reduction strategies as well as building the required capacity to monitor and manage climate variability and its impacts.

[1]Reference to African Union-United Nations Framework on Implementation of Agenda 2063 and Agenda 2030 and Africa Water Vision for 2025, UNECA.

Continued water infrastructure and technology investments and the introduction of relevant incentives by African governments are also needed, as are investments by the private sector and international financing agencies, all of which have a role to play. Climate change is likely to produce increased numbers and intensities of floods in many areas, with a variety of management actions required to improve flood management, including early warning systems and rehabilitation of degraded catchments and flood-proofing of water supply and sanitation infrastructure, to reduce the risk of subjecting vulnerable communities to a lack of drinking water and functioning sanitation facilities.

In other parts of the continent, investing in increased water storage infrastructure and other water provisioning infrastructure may be a higher priority to avoid and/or overcome water shortages and periods of drought. Increased investment and access to information about appropriate irrigation technology (e.g., drip irrigation, rainwater harvesting) may be required to improve effective water use and productivity at the farm level in the face of climate change. Shifting from rainfed to irrigated agriculture will protect rural livelihoods and food security in many areas. Artificial groundwater recharge in areas experiencing over-exploitation and degradation is also needed. Overall, a systematic scaling up of locally appropriate solutions is critical to ensure area- and region-wide poverty alleviation, climate change adaptation, and economic development.

Flexible planning to promote long-term adaptation to climate change is also necessary. This requires access to accurate climate change information for key water-related development planning departments (agriculture, mining, power generation, municipalities, etc.) and strong alignment and cooperation between water departments and those responsible for development planning. For basins and aquifers, the primary allocations are among riparian states. At the sub-basin or local level, multiple water allocation systems operate in Africa, with many parallel systems, both formal and customary. All must be sufficiently flexible and cooperative to enable water allocation adjustments that address climate variability in the face of national development objectives, with simultaneous consideration of capacity constraints.

Water stakeholders also must be involved in the water resource management process to ensure full support for any approach to be implemented; adequate and timely information exchange between stakeholders and responsible authorities is particularly crucial. Climate change adaptation ranges from creating major storage infrastructure down to the household level, particularly in areas that governments fail to reach consistently or effectively. The simple and timely provision of information can assist communities and households to prepare for anticipated changes, including the strategic selection of new crops to grow, improvement of cropping and livestock management techniques, local water resource use, and protection and flood warnings. Improving and sharing knowledge and information about climate change vulnerability and adaptation involves complex interactions among local land and water resource characteristics, economic conditions, and often diverse livelihood capitals and strategies of individual households.

These approaches depend on improved science and information-sharing, particularly across vulnerable transboundary basins and aquifers. A major challenge that

impacts Africa in particular is the weakness of models that predict climate change at the local level. Better modeling capacity is critical to ensure that management options and investment decisions are based on scientifically sound information. Accurately describing the current state, identifying emerging trends, and anticipating possible outcomes and associated vulnerabilities and risks also require appropriate monitoring systems to provide necessary data at an appropriate scale.

Against the backdrop of existing development challenges, substantial increases in financing to African countries are needed to improve land and water management systems and their capacity to adapt to climate change and to enhance resiliency. A range of new, innovative financing options is therefore required, including from government and private sources in developed countries.

A recurring theme in considering climate change is that no one is immune to its impacts, and that tackling it will require global collaboration, with emphasis on contributions from the industrial countries that have been responsible for most GHG emissions since 1850, and also from countries that are the current major contributors to GHG emissions. Wealthier developed countries, and major current GHG-emitting countries, must take the lead by

- Reducing their own GHG emissions, and meeting and/or exceeding the agreed emission targets;
- Meeting the financial commitments declared at global meetings and summits (i.e., ensuring that pronouncements made for political gain are matched by action and investment);
- Developing carbon pricing that provides incentives for transfer to sustainable sources of energy and phasing out perverse subsidies of all kinds;
- Implementing relevant measures to improve access by the poor to water, food, and energy; and
- Reviewing existing, and developing new, trade policies that support both development and technology transfer, in addition to training and capacity building, in Africa and developing countries elsewhere.

Overall, cutting emissions at their source aggressively, while addressing the impacts of global warming in the most vulnerable zones, is required. The obligation to act is therefore unequivocal: no matter what policy is in place; good intentions alone are not sufficient to address our grave imperative to take responsibility for emissions. There is an urgent need to act now to avoid severe climate change risks and impacts on water resources. At risk is nothing less than human livelihoods, as well as an existential threat to animal species that would likely be lost on an African continent that will soon be 2 °C warmer than pre-industrial levels.

Let's Act Now!

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Preface

The goal of *Climate Change and Water Resources in Africa* is to provide an overview of the many water resource management challenges, constraints, and opportunities for sustainable development in Africa. Water is very high on the agenda of the continent, particularly on issues of water supply and sanitation, and the water–energy–food nexus. Water is both an ecosystem 'good,' providing drinking water, irrigation and hydropower, and an ecosystem 'service,' enabling nutrient recycling and supporting habitats for fish and other aquatic organisms, as well as providing 'cultural services' such as scenic, recreational, and spiritual opportunities. Indeed, water is directly or indirectly important to almost every economic sector in Africa, including agriculture, manufacturing, trade, mining, tourism, and transport. The prospect of improving well-being in Africa is therefore critically dependent on its capacity to respond to water-related environmental changes—including climate change.

The IPCC recognizes Africa as one of the most vulnerable continents when it comes to the impacts of climate change—partly because of the projected nature of the climate change itself on the physical continent, and partly because of the significant levels of poverty and weak institutional capacity across the continent. Regarding the latter, the challenges of climate change overlay Africa's already fragile human and environmental conditions, with significant levels of poverty and service delivery that must be improved. Not only does climate change compound existing development pressures on limited water resources, but as climate change pressures intensify, they do so in the face of growing populations and economies, both of which place greater stress on existing water resources. Therefore, the challenge of managing water resources in Africa over the coming decades is both a climate change and a developmental challenge.

A consistent theme throughout the book is that the already-vulnerable poor population of Africa is most at risk from the impacts of climate change. The response must therefore focus in particular on increasing resilience at the household and community levels. Increased resilience will enable people, particularly those living in poverty, to respond effectively in order to recover faster from water-related disasters. The key elements of resilience are poverty eradication and access to appropriate information in a timely manner to support adaptation strategies. This approach will make climate change adaptation primarily a development challenge.

This book seeks to provide a basis for evidence-based policymaking, built on reliable data and sound information, to address the water-related challenges faced by Africa in the context of climate change and other stressors. It provides an overview of key water resources and climate change-related issues faced by Africa, including socioeconomic consequences, governance and understanding change in the context of institutional settings. The assessment is disaggregated first through a series of regional assessments, and subsequently in a series of detailed case studies, providing current scientific insight into various aspects of climate change-related freshwater challenges across the continent. The book furthermore discusses a number of tools and approaches for risk assessment and management. Finally, a number of critical research topics are proposed, including technology and innovation to address current and future challenges of climate change-related impacts on water resource management in Africa.

This book provides a platform for leading scientists from across the continent and beyond to contribute their expertise to address the challenges at hand. In this regard, we wish to thank the many contributors to this book for their relentless efforts and valuable contributions.

The Editors are extremely grateful to the African Academy of Sciences for supporting this project. The Editors are especially indebted to Elizabeth Marincola for her detailed editing of this book.

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Citations

"Action without thought is empty. Thought without action is blind"

Kwame Nkrumah (1909–1972), Prime Minister of Ghana from 1957 to 1960 and President of the Republic of Ghana from 1960 to 1966, and a Pan-African leader.

"there is unequivocal scientific evidence that our planet has been warming since the mid-20th century, primarily as a result of human activity. At the global level, we are still arguing about the sources and effects of climate change on the planet and on people, often driven more by self-interest than scientific evidence, while we in the developing world continue to suffer, even when we are not the culprits."

Amarakoon Bandara, Senior Economic Advisor, UNDP Zimbabwe in The Zimbabwe Human Development Report 2017 with a special focus on issues of climate change.

"rapid urbanization in Africa has placed enormous pressure on the continent's urban water supplies, and obviously this will likely be accentuated by the negative effects of climate change and its impact on freshwater resources. Effective solutions to urban Africa's water challenges can only succeed by improving water and sanitation infrastructure and by promoting integrated water and sanitation management… Viable solutions must be devised at the local level through a participatory approach involving all stakeholders. Indeed, community-based strategies including basic engineering to apply ecological principles and practices (for example, wastewater treatment and basic recycling of solid waste) is essential for addressing urban Africa's most acute water-related problems, especially in cities' most impoverished areas."

Salif Diop, from an interview provided to TWAS (The world academy of sciences for the advancement of science in developing countries) at the occasion of the World Water Day dedicated to Water and Cities—28 March 2011.

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Editors and Contributors

About the Editors

Prof. Salif Diop has worked at the United Nations, in UNEP's Division of Early Warning and Assessment (DEWA), for the past 16 years as Senior Officer. His water expertise is in coastal oceanography, freshwater assessment, aquatic and marine issues, sustainable management and development. He earned a Third-Cycle Doctorate in 1978 from the University Louis Pasteur in Strasbourg, France, and a State Doctorate in 1986. He served a year-long sabbatical as a Senior Fulbright Scholar in the Division of Biological and Living Resources at The Rosenstiel School of Marine and Atmospheric Sciences of the University of Miami, Division of Biological and Living Resources, in 1986/87.

He is a member of multiple expert and working groups and attached to numerous scientific and research institutions. He has published more than 40 peer-reviewed articles and 7 books as main author or co-author, and was awarded a Nobel Peace Prize Certificate in 2007 for his contributions to the IPCC. In addition to his research articles, he has also contributed 140 technical documents, research reports, monographs, theses, abstracts, and book reviews. He is currently a University Professor and has served as one of the Vice-Chairs of the International Lakes Environment Committee Foundation (ILEC) Scientific Committee since November 2016 and member of the High-Level Panel Expert Group for a Sustainable Ocean Economy related to the Sustainable Ocean Initiative of the World Resources Institute since September 2019. He was named a Member of

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Dr. Peter Scheren has been engaged in research, assessment, and management of both freshwater and marine ecosystems across Africa for over 25 years, in various parts of the continent. His passion is to bring the science, knowledge, and capacity for understanding of such systems together to guide policy, strategy, and governance systems that will help safeguard the ecosystem functions and values that strengthen the nature and the people that depend on them. He is the author and editor of many publications in this field.

He holds a Ph.D. from the University of Eindhoven and the University of Wageningen in the Netherlands, with a focus on Integrated Environmental Assessment of Water Systems. He has worked for various research institutions, consultancy offices and international organizations, and has managed several large-scale freshwater and marine programs in Africa for WWF, UN Environment, UNIDO, and UNDP. He is currently active as a freelance consultant, based in France, supporting the development of a range of strategic, transformational projects, and programs for WWF in their various fields of work across Africa.

Dr. Awa Niang is an Associate Professor of Continental Hydrology at Cheikh Anta Diop University, in Dakar, Senegal. She holds a first doctoral thesis from Cheikh Anta Diop University, with a focus on water quality management of Guiers Lake (Senegal River Delta). In 2014, she also earned a Ph.D. on recent hydrological and morphological changes in the Senegal River Estuary.

Her recent work focuses on the vulnerability and resilience of the coastal social ecosystems of the Senegal River Estuary. She participates in various projects and programs dealing with Integrated Water Resource Management, remote sensing applied to water resources

and environmental management, and coastal and estuarine studies. She contributes to the design, implementation, and management of the Doctorate School on Water Quality and Uses. She leads the scientific Secretariat and communications of the doctoral school since its creation in 2008 and is now coordinating doctoral studies on continental hydrology and integrated water resource management. Since 2010, she was involved in the ACEWATER (African Networks of Centres of Excellence on Water Sciences) Project. Currently, in its second phase (ACEWATER2), the project is promoted by the African Ministers of Water, financed by DG DEVCO, implemented by DG JRC (project management and scientific cluster) with UNESCO (human capacity development cluster). The project aims at supporting the establishment of Human Capacity Development Programme of the AMCOW (African Ministers' Council on Water) in the Water Sector, strengthens institutional networking and improving research support to policymaking addressing the WEFE (Water–Energy–Food–Ecosystem) nexus. She is actually acting as coordinator of the Western Africa network (WANWATCE) of the Centers of Excellence on Water Sciences and Technology.

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Chapter 4
Climate Change and Water Resources in West Africa: A Case Study of Ivory Coast, Benin, Burkina Faso, and Senegal

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Abstract Climate change is a major challenge for humanity due to its numerous impacts on people and the environment, which requires multiple strategies to address it. West Africa, particularly Ivory Coast, Benin, Burkina Faso, and Senegal are confronted with the full impact of that challenge. This study seeks to analyze climate

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change by looking at the climate characteristics and rainfall duration recorded at forty selected stations. Senegal and Burkina Faso stretch over three climatic zones that include the Sahelian zone in the North, the North-Sudanian zone in the center, and the South-Sudanian zone in the South. For Ivory Coast and Benin, the northern and central areas are, respectively, located in the North-Sudanian and South-Sudanian climate zones, whereas the South is covered by the Guinean zone. In all four countries, break tests and water balance are characterized by the Standardized Precipitation Index, which measures changing water resources. Our research shows significant rainfall variability, with important impacts on water resources. For data from Ivory Coast from 1921 to 2016, there occurred a sharp decrease in the early 1980s; a similar decrease occurred in the late 1960s in Benin, Burkina Faso, and Senegal. This led to a noticeable decrease in surface water, while underground water, especially deep water, was less affected. However, a slight increase in rainfall is noted in Burkina Faso and Senegal in the 1990s. As local populations have grown aware of the negative effects of rainfall changes, they have initiated action to protect and manage water resources in a sensible and efficient way to preserve incomes from farming, grazing, and fishing. For this context, implementation of appropriate strategies likely to alleviate the harmful consequences of climate change must be tackled head-on. This can only be achieved through a wider knowledge of climate trends, coordination of stakeholders, and a broader dialogue to find the best communal solutions.

Keywords Climate change · Water resources · Impacts · Adaptation strategies · West africa

1 Introduction

Climate change is a global challenge for humanity because of its devastating impacts and the multiple adaptation and mitigation strategies required to address it. West Africa in general, and more acutely Ivory Coast, Benin, Burkina Faso, and Senegal, suffers particular effects of climate change with a rise in temperatures, irregular rainfall, variable rainy seasons, sea-level rise with significant coastal erosion, decrease in water resources, etc. Given the importance of farming and its role in the economic and social development of these countries, the major climate characteristics of this area remain the spatio-temporal and interannual changes in precipitation, which have become a permanent concern for local populations.

Indeed, since the severe drought (Leroux 1995) of the Sahelian zone, which began in 1968 and gradually spread to the South, including the Sudanian and Guinean zones (Sagna et al. 2015), the four countries selected for this study are experiencing a climatic and environmental crisis that jeopardizes their future in many sectors.

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Important studies have been conducted that lend a better understanding of precipitation and climate dynamics of circulation and rainstorms (Leroux 1995; Sagna 2005; Leroux 2010; Sagna et al. 2012, 2018). The spatio-temporal evolution of rainfall, including effects of drought in the 1970s and 1980s, is also well documented (L'Hôte et al. 2002; Nicholson et al. 2012; Kaboré et al. 2017). Research on runoff has shown a decrease in flows, directly correlated with a decrease in rainfall (Oyebande and Odunuga 2010). Groundwater is also affected by rainfall variability (Barrat 2012; Hammond Murray-Rust and Fakhruddin 2014). Other studies emphasize the importance of rainwater for human activity in West Africa (Diop 1999; Sène 2007; Sané et al. 2008; Sultan 2011; Diallo et al. 2012; Camara et al. 2013; Sagna et al. 2015; Sultan et al. 2015; Sané 2017), demonstrating the dependence of rural livelihoods on rainwater, especially over the last fifty years, as well as the negative impacts of irregular rainfall on rural development and the living conditions of farmers. The impacts of climatic hazards have also been a major political and scientific concern (Sultan et al. 2015; Sané 2017), insofar as the socioeconomic foundation of the region rests on factors directly or indirectly dependent on climatic conditions: farming, grazing, and fishing. Strategies to address climate hazards have been analysed (Houssou-Goé 2008; Kpadonou et al. 2012; Vissin 2013; Sambou 2015; Dipama 2016; Gautier and Denis 2016; Callo-Concha 2018). Gautier and Denis 2016 reviewed literature on adaptation in West Africa based on 37 publications on Senegal, 66 on Burkina Faso and 18 on Benin—three of the four countries included in our study. These studies reveal that the most studied sector is farming. They entail changes in crops and varieties, as well as changes in practices such as sowing period, water conservation techniques, and relocation of fields, to conserve and optimize water.

Despite the significant amount of research on climate change and its impacts and adaptation strategies for West Africa, some issues remain unclear, especially on the current trend of rainfall and its manifestations that affect the livelihoods of local communities who still depend on rainwater. The consequences of interannual variations in rainfall significantly influence water resources with all the attendant consequences for the livelihoods of broad populations, especially subsistence farmers. Given this critical situation, the current state of climate change must be studied in West Africa, particularly in Ivory Coast, Burkina Faso, Benin, and Senegal, because of the poor quality of available information.

The aim of this study is to analyze the trend of annual rainfall variations and their tangible impacts on the environment. This will be achieved by the analysis of time-series data from the four selected countries, as well as by observations of water flows and groundwater. The impacts of water deficit and water excess on socioeconomic activities will also be studied, and potential strategies to improve response to changes in water resources in the context of climate change will be discussed.

2 Data and Methodology

2.1 The Four Countries Included in the Study

The four countries chosen for this study, Ivory Coast, Benin, Burkina Faso, and Senegal (Fig. 1), experience climatic similarities and differences. The similarities are in circulation mechanisms and disturbances; the differences are mainly related to rainfall and temperature. As for surface atmospheric circulation, trade wind and monsoon circulations have been observed to alternate, contributing different proportions of wind frequencies. Average flows for the year 2014 illustrate this alternation:

- 13.8% for trade wind and 86.2% for monsoon in Ivory Coast;
- 18.4% for trade wind and 81.6% for monsoon in Benin;
- 40.5% for trade wind and 59.5% for monsoon in Burkina Faso, and
- 58% for trade wind and 42% for monsoon in Senegal.

Precipitation is mainly from squall lines, especially in Senegal and Burkina Faso, while the proportion from the Intertropical Convergence Zone (ITCZ) is very high in the south of Ivory Coast and Benin. There are also orographic and thermal factors, as well as cyclonic disturbances, all of which have impacts on precipitation. Overall, given the dynamics of precipitation, the southern countries (Ivory Coast and Benin) have higher levels of rainfall than the northern countries (Burkina Faso and Senegal).

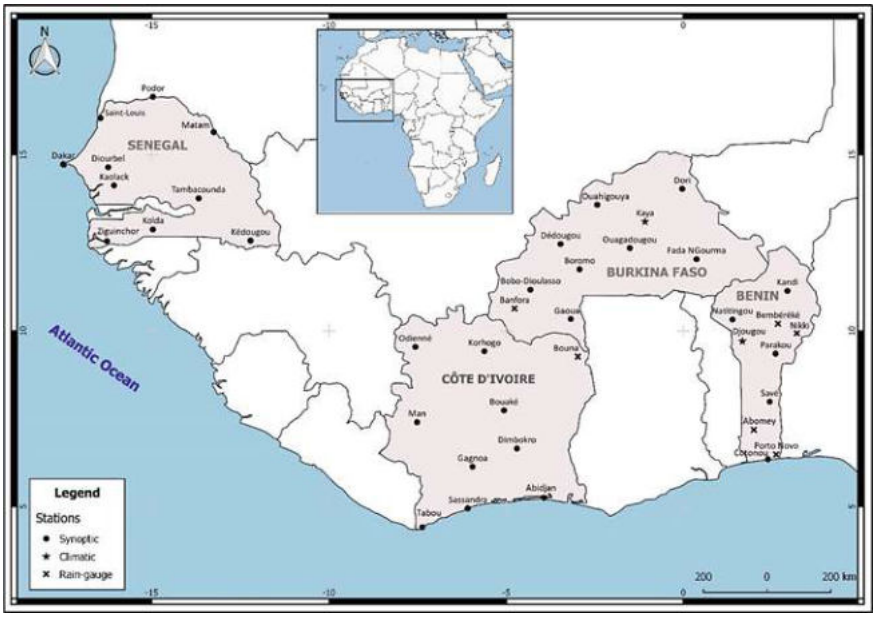


Fig. 1 Countries studied

Therefore, in terms of recorded rainfall and rainy seasons, there are three climatic zones in Senegal and Burkina Faso: the Sahelian zone in the north, the North-Sudanian zone in the center and the South-Sudanian zone in the south. For Ivory Coast and Benin, the South-Sudanian zone spans the northern and central areas while the southern area is located in the Guinean zone. In those countries, interannual variability of rainfall was used to determine the evolution of water resources and especially their scarcity because of drought that recurs in the area.

2.2 Data

In each of the four countries, ten stations were selected based on their geographic distribution, time-series lengths, meteorological significance, and data reliability. There were a total of forty stations (Fig. 1 and Table 1).

At most stations, observations began in the 1920s. For consistency, the study applied a starting year of 1921 and ending year as 2016 for all four countries, a time series of 96 years. The data came from various national meteorological services in the countries and the Inter-African Committee of Hydraulic Studies through the Overseas Office of Scientific and Technical Research (ORSTOM). For each country, the Standardized Precipitation Index (SPI) was calculated to determine if a given year is in excess (SPI > 0) or in deficit (SPI < 0) of the baseline standard. Although the SPI has been designed to detect droughts and is still widely used to characterize dry phases (Agnew 2000; WMO 2016), it allows an estimation of both dry and wet periods (McKee et al. 1993; WMO 2012), thus enabling the determination of breaks and phases in rainfall. The SPI is calculated as follows:

$$\mathbf{SPI} = \frac{\boldsymbol{P} - \bar{P}}{\boldsymbol{\sigma}} \tag{1}$$

- where **P** is the average rainfall of the year in the country;
- $\bar{P}$ is the average rainfall in the 1921–2016 time series in the country; and
- **σ** is the standard deviation of the annual rainfall series in the country.

Rainfall-break detection remains important in any analysis of climate change. Rainfall series were subjected to Pettitt's (1979) and Lee and Heghinian's (Lee and Heghinian 1977) break-detecting tests. Pettitt's approach is nonparametric because it makes no assumptions about the underlying distribution of data derived from the Mann–Whitney test (Pettitt, 1979). Pettitt's procedure is applied here to certify the research findings of our study. As a result, the absence of a break in the series (xi) of size T constitutes the null hypothesis (no break in the time series). When conducting this test, we assumed that for any moment t between 1 and T, the time series (xi) i = 1 at t and t + 1 at T belong to the same population. The variable to be tested is the maximum in absolute value of the variable Ut, with T defined by

Table 1 Stations in the four countries of the study area

Country	Station	Latitude	Longitude	Altitude (m)	Type of station
Ivory Coast	Odienné	09° 30' N	07° 34' W	432	Synoptic
	Korhogo	09° 27' N	05° 38' W	300	Synoptic
	Bouna	09° 16' N	03° 00' W	316	Rain-gauge
	Bouaké	07° 41' N	05° 02' W	369	Synoptic
	Man	07° 24' N	07° 31' W	340	Synoptic
	Dimbokro	06° 39' N	04° 42' W	110	Synoptic
	Gagnoa	06° 08' N	05° 57' W	205	Synoptic
	Tabou	04° 25' N	07° 22' W	4	Synoptic
	Sassandra	04° 57' N	06° 05' W	50	Synoptic
	Abidjan	05° 15' N	03° 56' W	7	Synoptic
Benin	Kandi	11° 08' N	02° 56' E	290	Synoptic
	Bembéréké	10° 12' N	02° 40' E	491	Rain-gauge
	Natitingou	10° 19' N	01° 23' E	460	Synoptic
	Nikki	09° 56' N	03° 12' E	402	Rain-gauge
	Djougou	09° 42' N	01° 40' E	439	Climatic
	Parakou	09° 21' N	02° 36' E	392	Synoptic
	Savé	08° 02' N	02° 29' E	198	Synoptic
	Abomey	07° 11' N	01° 59' E	260	Rain-gauge
	Porto-Novo	06° 29' N	02° 37' E	20	Rain-gauge
	Cotonou Ville	06° 21' N	02° 26' E	5	Rain-gauge
Burkina Faso	Dori	14° 02' N	00° 02' W	288	Synoptic
	Ouahigouya	13° 35' N	02° 26' W	329	Synoptic
	Kaya	13° 06' N	01° 05' W	313	Climatic
	Dédougou	12° 28' N	03° 28' W	308	Synoptic
	Fada Ngourma	12° 04' N	00° 21' W	292	Synoptic
	Ouagadougou	12° 22' N	01° 31' W	296	Synoptic
	Boromo	11° 44' N	02° 55' W	264	Synoptic
	Bobo-Dioulasso	11° 10' N	04° 18' W	432	Synoptic
	Gaoua	10° 20' N	03° 11' W	333	Synoptic
	Banfora	10° 37' N	04° 46' W	270	Rain-gauge
Senegal	Podor	16° 38' N	14° 56' W	7	Synoptic
	Saint-Louis	16° 03' N	16° 27' W	4	Synoptic
	Matam	15° 38' N	13° 15' W	15	Synoptic
	Dakar	14° 44' N	17° 30' W	27	Synoptic
	Diourbel	14° 39' N	16° 14' W	7	Synoptic
	Kaolack	14° 08' N	16° 04' W	6	Synoptic

(continued)

Table 1 (continued)

Country	Station	Latitude	Longitude	Altitude (m)	Type of station
	Tambacounda	13° 46' N	13° 41' W	49	Synoptic
	Ziguinchor	12° 33' N	16° 16' W	26	Synoptic
	Kolda	12° 53' N	14° 58' W	35	Synoptic
	Kédougou	12° 34' N	12° 13' W	165	Synoptic

(ORSTOM 1973)

$$U_{t,T} = \sum_{i=1}^{t} \sum_{j=t+1}^{T} D_{ij} \tag{2}$$

where

- D_{ij} = sgn(Xi-Xj) with sgn(X) = 1 if d > 0; 0 if d = 0, and -1 if d < 0.
- With d = Xi - Xj.

The rejection of the null hypothesis supposes an estimation of the date of break which is given by the moment t which defines the maximum in absolute value of the variable $U_{t,T}$. This tool is used regularly because of its precision and robustness, as well as assurance of high levels of reliability.

The hypothesis of a relatively wet period in the countries selected for this study is also verified with Hubert's segmentation procedure (Hubert et al. 1989). Tests for detecting breaks and the segmentation procedure were applied with KhronoStat software developed by the *Maison des Sciences de l'Eau* of the Research Institute for Development (Boyer 2002).

Several climate and hydrologic models have been used to analyze rainfall and water resources, particularly in West Africa. These models include, for example, the Regional Climate Models (RCMs) and the Global Climate Models (GCMs), the hydrologic model GR2M and the Water Flow and Balance Simulation Model (WaSiM). Based on relatively well-calibrated reference situations, projections of rainfall and water resources improve management of water resources.

Surveys were carried out in several areas and on many aspects of the lives of both rural and urban populations, so as to better understand the impacts of current climate change on socioeconomic activities. Endogenous and state strategies are also deployed by several stakeholders to address climate change. Findings vary in their relevance and effectiveness from one country to another, and from one local area to another.

3 Research Findings

3.1 Interannual Rainfall Variability

Application of the different statistical tools on rainfall records in the 96-year study period resulted in findings that differed among the four countries.

Rainfall in Ivory Coast showed two break years in the study period: 1981 for the Standardized Precipitation Index and Pettitt's test, and 1982 for Lee and Heghinian's test (Figs. 2, 3, and 4). Compared to the former, the latter two have periods of unequal duration with different characteristics. The wet period, which extends from 1921 to 1981, shows an average rainfall of 1538 mm, while the dry period, from 1982 to 2016,

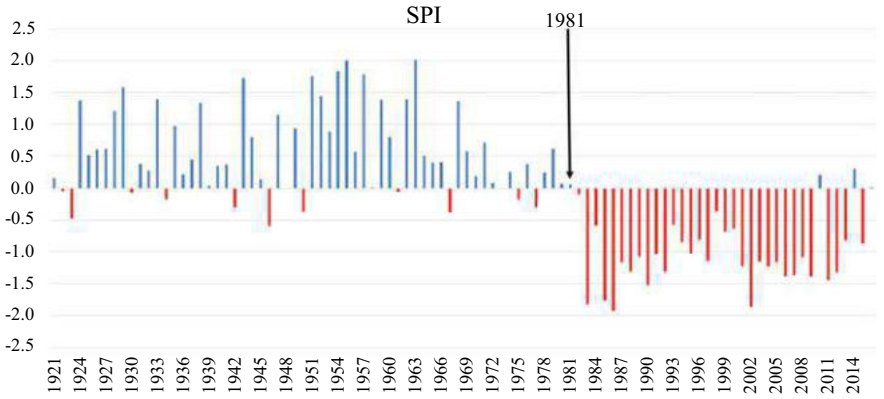
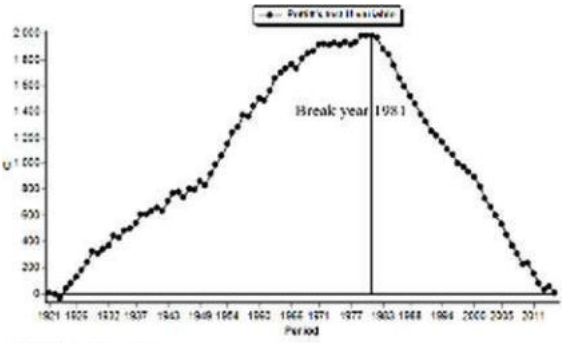


Fig. 2 Evolution of the Standardized Precipitation Index in Ivory Coast from 1921 to 2016

Fig. 3 Evolution of Pettitt's test results in Ivory Coast from 1921 to 2016



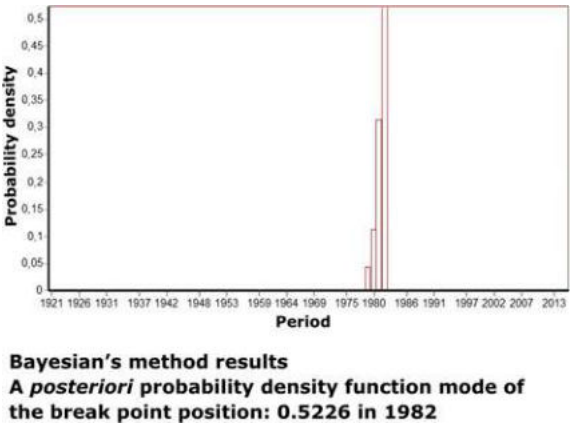


Fig. 4 Evolution of Lee and Heghinian's test results in Ivory Coast from 1921 to 2016

shows an average of 1139.8 mm. The difference between the two periods is 398.2 mm, which corresponds to a drop of 25.9% in rainfall. The rainiest years are concentrated between 1951 and 1963: 1951 with 1833.5 mm, 1954 with 1851.3 mm, 1955 with 1893.7 mm, 1957 with 1838.7 mm and 1963 with 1895 mm. The driest years, apart from 2002 (928.2 mm), are also close to one another: 1983 with 937.3 mm, 1985 with 952.5 mm, 1986 with 911.3 mm and 1990 with 1011.4 mm. Between the wettest year (1963) and the driest year (1986), the difference is 983.7 mm. In the entire series, 51 years are in excess and 45 years in deficit. Rainfall seems to continue to diminish.

In Benin, the application of the Standardized Precipitation Index and the tests of Pettitt and Lee and Heghinian reveal a break in 1969 within the series from 1921 to 2016 (Figs. 5, 6, and 7). Two periods stand out in this period: the first, which extends for 49 years from 1921 to 1969, with an average rainfall of 1276.5 mm, is wet, while the second, which extends for 47 years, between 1970 and 2016 with an average rainfall of 1122.1 mm, is dry. The difference between the two periods is

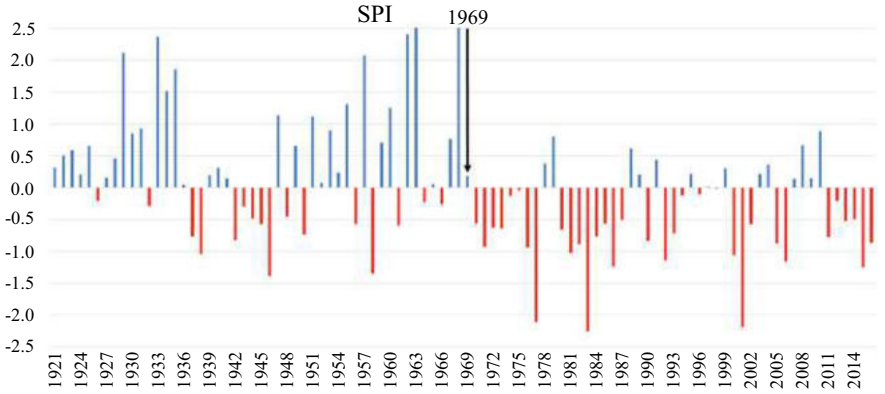


Fig. 5 Evolution of the Standardized Precipitation Index in Benin from 1921 to 2016

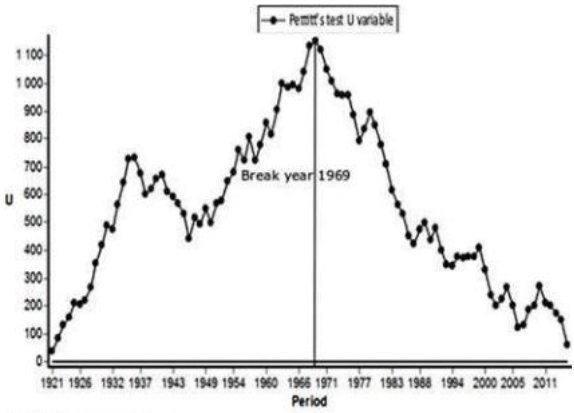


Fig. 6 Evolution of Pettitt's test results in Benin from 1921 to 2016

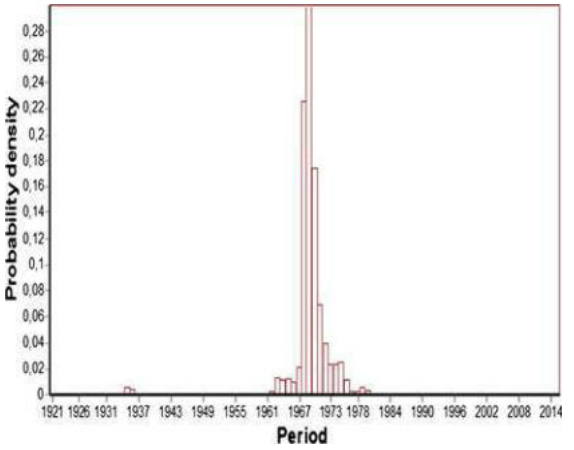


Fig. 7 Evolution of Lee and Heghinian's test results in Benin from 1921 to 2016

154.4 mm: 12.1%. The six rainiest years, with an SPI higher than 2, are found in the first period, with 1567 mm in 1929, 1611.3 mm in 1933, 1561.1 mm in 1957, 1618.9 mm in 1962, 1647.5 mm in 1963, and 1683.7 mm in 1968. The driest years are more scattered, with 960.8 mm in 1946, 967.8 mm in 1958, 835 mm in 1977, 809.7 mm in 1983, and 821 mm in 2001. The difference between the wettest year (1968) and the driest year (1983) is 874 mm. Overall, analysis of the rainfall series

reveals 47 years of excess, including 33 in the first period and 14 in the second, and 49 years of deficit, including 16 in the first period and 33 in the second. More recent years remain affected by drought.

In Burkina Faso, from the years 1921 to 2016, there was a rainfall break in 1969, confirmed by the Standardized Precipitation Index, the tests of Pettitt and Lee and Heghinian, and by the segmentation of Hubert (Figs. 8, 9, and 10). Thus, we found that the period from 1921 to 1969 was on the whole wet, with an average rainfall of 927.4 mm, marked by a dry period between 1970 and 2016, despite a significant increase from 2008 to 2016, with an average of 805.3 mm. The difference in rainfall between the two periods mentionned above is 122.1 mm and corresponds to a decrease in rainfall of 13.2%. The wettest years are scattered within the first period, with 1033.6 mm in 1922, 1064.6 mm in 1933, 1044.9 mm in 1951, 1048.7 mm in

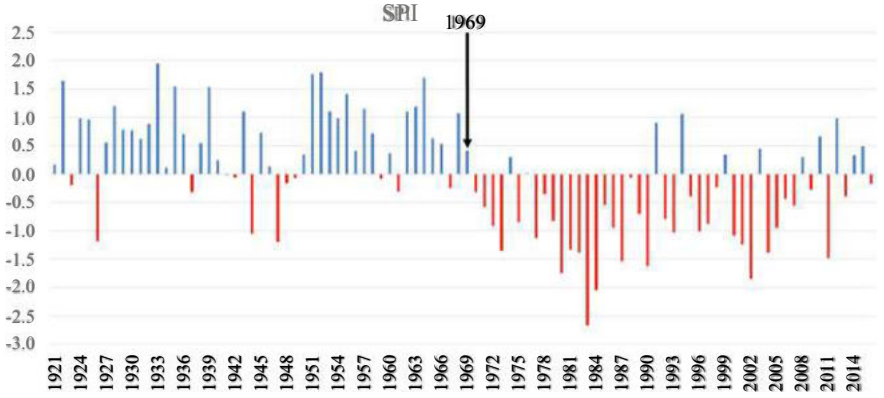
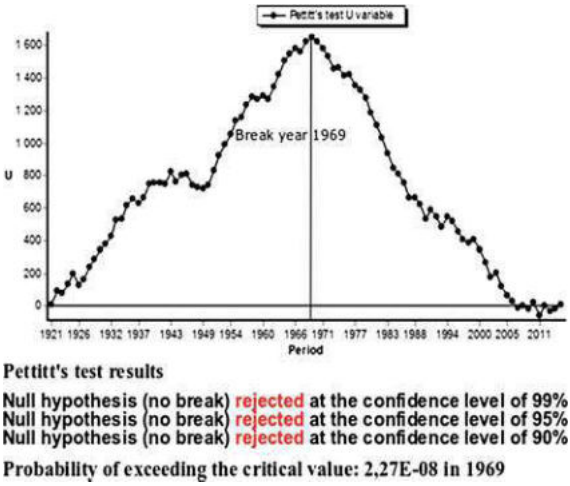


Fig. 8 Evolution of the Standardized Precipitation Index in Burkina Faso from 1921 to 2016

Fig. 9 Evolution of Pettitt's test results in Burkina Faso from 1921 to 2016



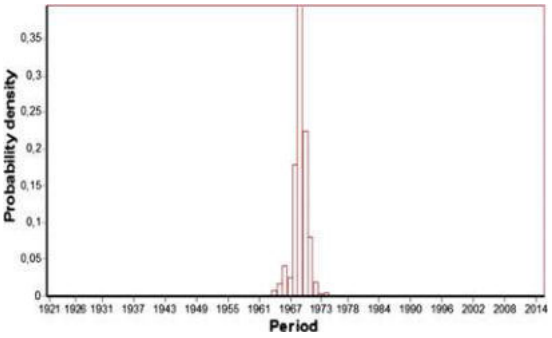


Fig. 10 Evolution of Lee and Heghinian's test results in Burkina Faso from 1921 to 2016

1952, and 1039.3 mm in 1964. The driest years in the second period are closer to each other, with 691.5 mm in 1980, 598.5 mm in 1983, 662.6 mm in 1984, 704.4 mm in 1990, and 681.6 mm in 2002. The difference between the rainiest year (1933) and the driest year (1983) is 466.1 mm. This series of rainfall measurements in Burkina Faso is on average 48 years greater than the average of the period 1921–2016, with 37 years in the wet period and 11 years in the dry period and 48 years lower, including 12 in the first period and 36 in the second. Despite this relative balance, recent years have marked an increase in rainfall.

In Senegal, the Standardized Precipitation Index and the tests of Pettitt and Lee and Heghinian indicate a rainfall break in 1967 (Figs. 11, 12, and 13). The break reveals two major periods: a generally wet period from 1921 to 1967, and a relatively dry period from 1968 to 2016. The average rainfall is 832 mm for the first period and

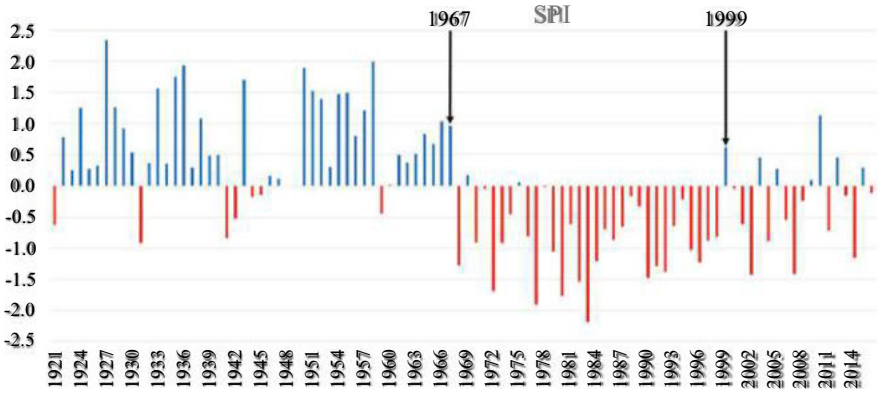


Fig. 11 Evolution of the Standardized Precipitation Index in Senegal from 1921 to 2016

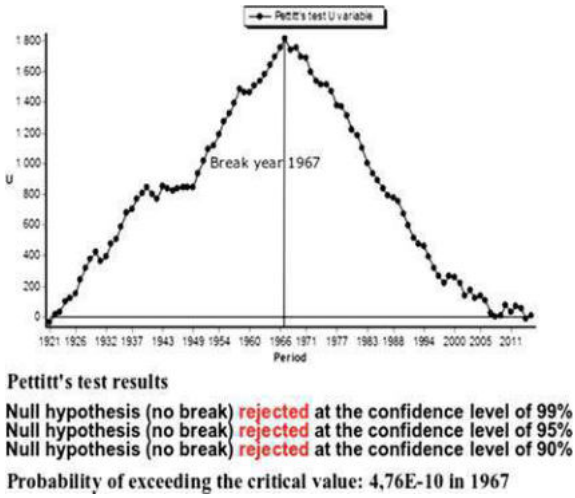


Fig. 12 Evolution of Pettitt's test results in Senegal from 1921 to 2016

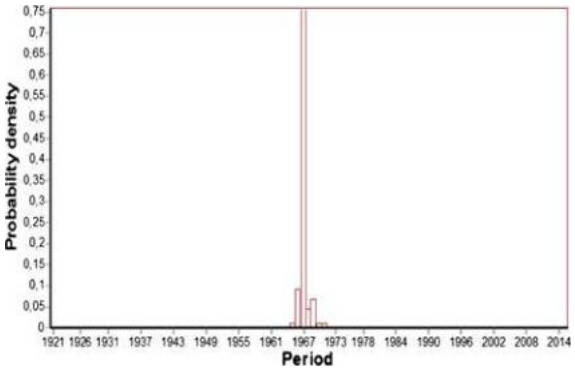


Fig. 13 Evolution of Lee and Heghinian's test results in Senegal from 1921 to 2016

639.4 mm for the second—a rainfall decrease of 192.6 mm (23.1%). The rainiest years were 1927, 1936, 1950, and 1958, with respective rainfalls of 1076.5 mm, 1016.6 mm, 1011.2, mm and 1026 mm. The driest years were 1972, 1977, 1980, and 1983, with respective rainfalls of 488.1 mm, 456.3 mm, 475.8 mm, and 414.9 mm. The difference between the wettest year and the driest year was 661.6 mm. The dry period, the beginning of which was confirmed in 1968 by the segmentation of Hubert, was subdivided into two sub-periods, the first extending from 1968 to 1998 with an average rainfall of 603.3 mm, and the second from 1999 to 2016 with an average of 701.6 mm. The 1999–2016 sub-period represents a slight increase in rainfall of 98.3 mm (14%) compared with the previous period. Over the entire series, 47 years

are in excess, of which 38 are during the wet period, and 49 years are in deficit, of which 40 are during the dry period. It is notable that droughts still occur in Senegal.

3.2 Impacts of Rainfall Variation on Water Resources

The alignment of rainfall analyses with reality is visible by the impacts of changes in water resources on livelihoods. It is imperative to be able to predict the supply of and demand for water resources over a given period to be able to create and maintain sustainable and efficient water management.

3.2.1 Impacts of Rainfall Variation on Runoff and Lakes

In Ivory Coast, an overall downward trend in water resources correlates with a decrease in rainfall. For example, in the Sassandra River basin, Coulibaly et al. (2018) used the Representative Concentration Pathway (RCP) 4.5 and RCP 8.5 climate models and the Regional Climate Model 4 (RegCM4) of the Abdus Salam International Center for Theoretical Physics (ICTP) to obtain data to integrate into the GR2M hydrologic model. By 2030, 2050, 2070, and 2090, annual flows will decrease compared to the 1961–1980 reference period. The decline in flows follows the same progression as the climate projections of the RegCM4 model. The RCP models 4.5 and 8.5 also show a decline of 6.9–24.1% in flows from the Guinean source to the Ivorian parts of the Sassandra between 2030 and 2090. According to Koffi and Diomandé (2015), Lake Kossou (a reservoir on the Bandama River in Central Ivory Coast) declined by 37.4%, a loss of 20,394 hectares (Fig. 14). Its area has decreased from 54,583 hectares in 2002 to 34,189 hectares in 2014.

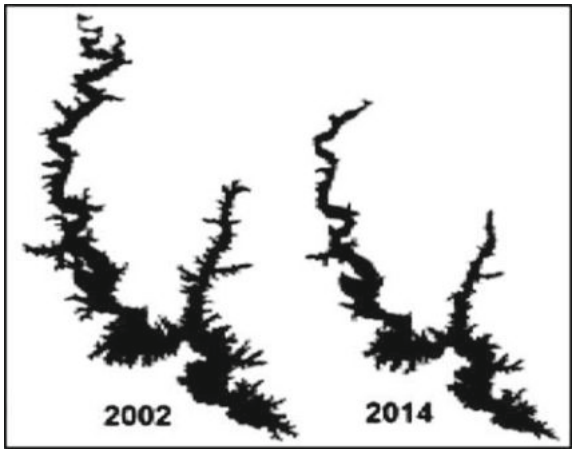


Fig. 14 Comparative area of Lake Kossou between 2002 and 2014

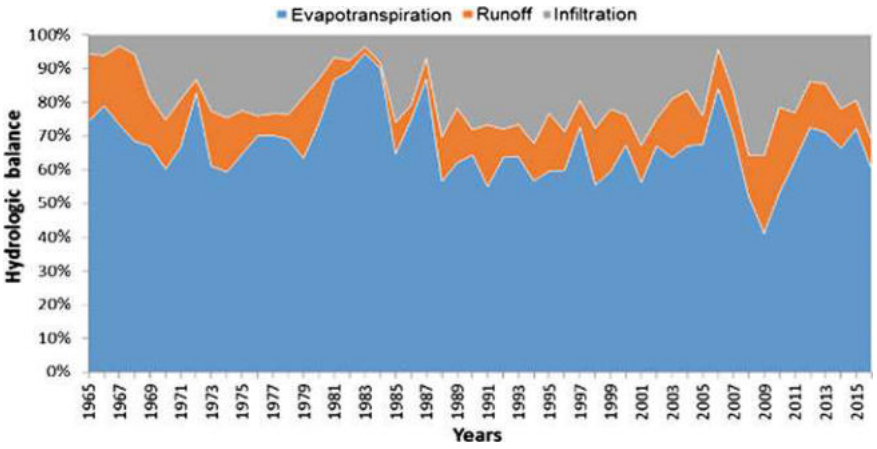


Fig. 15 Hydrologic balance of the Ouémé basin from 1965 to 2016

In Benin, the hydrologic balance of the Ouémé basin from 1965 to 2016 indicates that evapotranspiration accounts for ≥50% of the hydrologic balance annually, whereas storage is around 35–40% (Fig. 15). As a result, the majority of rainfall evaporated, while 11–13% became runoff. These findings align with the simulated findings (TopAMMA) from Le Lay (2006), which found that evapotranspiration was 50% and runoff was 12%, with underground stock change of 38%. There was a decrease in flow during dry years (early 1970s and 1980s). Water balance in the series showed an increase in evapotranspiration during those years, while runoff and infiltration decreased. The output of the BenHydro model (Speth et al. 2010) for the entire Ouémé River basin clearly shows the impact of the decrease in rainfall on surface runoff by 2050. From 1980 to 2050, the model predicts a steady decline in the flows of the Ouémé at Bonou, except for 2031–2040, that shows a slight increase (MEPN 2008) (Fig. 16). By combining 65 projections of 24 climate models, Essou and Brissette (2013) demonstrate that annual flows of the Ouémé will drop by 3–5% by 2099.

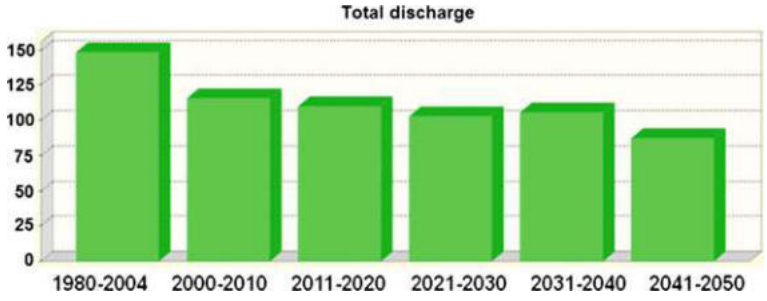


Fig. 16 Evolution of discharges of the Ouémé at Bonou at different time horizons (MEPN 2008)

In the event of an increase in the duration and frequency of dry seasons and decrease in rainfall in the upper basin of the Ouémé River and the Beninese Niger River basin as reported by MEHU (2011) and Lawin et al. (2013), there will be a negative impact on the availability of water resources. For example, a decrease in rainfall can lead to a decrease in runoff. This could also be accompanied by a reduction in the amount of water stored in natural or constructed reservoirs into which seasonal rivers flow. Hence, there is a likelihood of recurrent drying of water reservoirs as was the case in 2014 for the Djougou reservoir. In the Beninese part of the Niger River basin and in the central and southern regions, a decrease in rainfall could lead to a decrease in runoff. The late onset of rainy seasons could introduce a delay in the occurrence of high-flow periods.

Runoff decreases with rainfall in the Burkinabe parts of the Niger and Volta basins (El Vilaly and El Vilaly 2013). In the Dapola basin, there was a 1.5% decrease in decadal discharges after 1971. Yira et al. (2017) used a set of six regional and global climate models (RCMs and GCMs) to predict future rainfall and runoff in the Dano basin. The data are then integrated into the Water Flow and Balance Simulation Model (WaSiM). Two scenarios of greenhouse gas concentrations (the Representative Concentration Pathways RCP 4.5 and RCP 8.5) were selected. Findings show that there are uncertainties about the rainfall and runoff relationship in the basin over the period 2021–2050 compared to the period 1971–2000.

In the Senegal River basin, the relatively dry period from 1960 to 1996 resulted in a decrease of 30–40% in water availability following a decrease of 20% in rainfall (Oyebande and Odunuga 2010). In the upper basin, the average discharge during 1971–2010 (after the rainfall break) decreased by 34–54%, depending on the waterway, compared to 1904–1969 discharges (before the break). The HadRM3P and RCA climate models and the GR2M hydrologic model allow us to estimate climatic and hydrologic changes. They show a general downward and cyclical trend of flows for the 2030, 2060, and 2090 horizons compared to the 1961–1990 period (Diakité 2017). In fact, variations in flows are twice as high as changes in rainfall (Le Lay and Galle 2005). Magistro and Lo (2001) find a halving of the flows of the Senegal River between the 1950s and the 1990s. Bodian et al. (2013) used four 2007 models by the IPCC and a hydrologic model (GR2M) to study the impact of climate change on the upper Senegal River basin. According to three climate models (CSMK3, HadCM3 and MPEH5), there will be a gradual decrease in discharge from 2030 to 2090 (Bodian et al. 2013). Mbaye et al. (2015) used the regional climate model REMO as input to the Max Planck Institute Meteorology-Hydrology Model (MPI-HM) to simulate flow rates, runoff, soil moisture, and evapotranspiration. They found a drastic decrease of 50% in water resources in the upper Senegal River basin. The decrease is more pronounced toward the North. To the South (Guinean Highlands), models do not show any variation in water resources. Decline in water resources is related to the decrease in rainfall and the increase in potential evapotranspiration (Mbaye et al. 2015).

3.2.2 Impacts of Rainfall Variation on Groundwater Levels

In West Africa, data collected between 1992 and 2005 by the AMMA project (Multidisciplinary Analysis of the African Monsoon) show that there is no direct correlation between annual rainfall and groundwater recharge. This is due to the intensity of precipitation, which is more decisive. Moderate rains lead to more infiltration than intense and light rains (Hammond Murray-Rust and Fakhruddin 2014). Estimating the impacts of precipitation on groundwater is difficult to achieve in West Africa because locally collected data are scarce and the rates of change in rainfall, runoff, and infiltration can be highly variable, even in small areas. However, we note that anthropogenic factors, particularly irrigation, have a greater influence on the decrease in groundwater levels than climate change, according to a simulation in Mali. The increase in the groundwater level of the Continental Terminal in Niger averaging 0.2 m/year since the 1960s shows that the climate-groundwater relationship is not simple (Barrat, 2012).

In Benin, the comparative analysis of the two representations (Fig. 17) demonstrates the dynamics of Lake Nokoué bathymetry between 1980 and 2004.

The analysis of bathymetry maps made by Tessier (1980) (at left) and Dakpogan (2005) (at right) shows that Nokoué Lake experienced depth decreases between 1980 and 2004. In 1980, depths reached about 2 m in the West and in the North. But in 2004, depths dropped below 2 m. Only in the central depression and at the entrance of the channel did they reach or exceed 2 m (Dakpogan 2005).

The 1970s and 1980s were characterized by a decline in groundwater recharge. Sites at Ouagadougou (Burkina Faso) in 1987 and Fô-Bouré (Benin) in 2006 showed a decrease in groundwater. Deep groundwater is less affected because its recharge process is more complex. In the Volta basin, assuming no change in water demand, groundwater recharge is projected to drop by approximately 50% in the 2100 horizon, in relation to a temperature increase of 3.8 °C and a rainfall increase of 20% (Hammond Murray-Rust and Fakhruddin 2014).

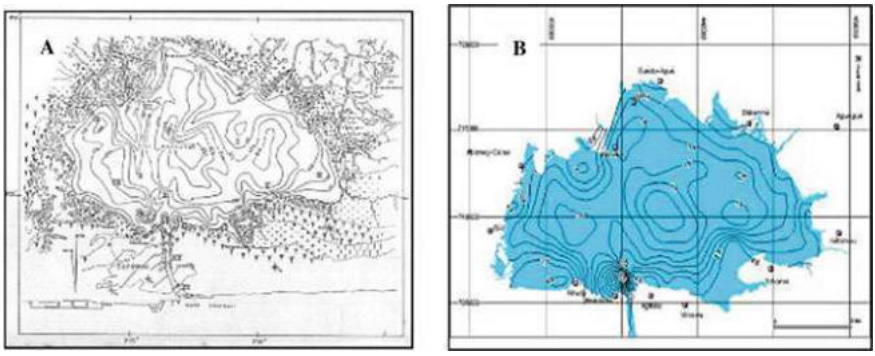


Fig. 17 Bathymetry of Lake Nokoué in 1980 (**a**) (Tessier 1980) and 2004 (**b**) (Dakpogan 2005)

In Senegal, the impact of the rainfall deficit on groundwater resources has been greatest on the northern coast (the Niayes) where almost all of the country's truck farms are located. In this location, decreases in groundwater levels occurred mainly in the 1970s and 1980s (Aguiar et al. 2010; Sambou 2015): the droughts of the 1970s and 1980s caused the groundwater level to decrease from 50 to 22 m between 1958 and 1984 (Aguiar et al. 2010). Malou (2004) noted that this was the most severe documented drying trend of groundwater reserve. During the droughts, groundwater recharge was very low (Dasylva and Cosandey 2005). Moreover, the drop was exacerbated by losses through evapotranspiration. On the horst of Ndiass (far south of the northern coast), the fall in groundwater levels, over the last 25 years, caused mainly by human activity, varied from 20 to 25 m (MEPN 2005).

The combination of declining rainfall, increased temperature (evaporation and evapotranspiration), the intensity of showers (which favors runoff to infiltration), and the multiple human uses of water result in scarce resources and low groundwater levels globally. The drying up of wells in many villages is evidence of this phenomenon.

3.3 Impacts of Rainfall Variation on Socioeconomic Activities

Rainfall variability has repercussions for farming, grazing, and fishing in West Africa. Impacts vary from one crop to another and by region.

3.3.1 Impacts of Rainfall Variations on Farming

In Ivory Coast, farmers mainly plant two types of crops: cocoa, a perennial crop grown in the southern forest area, and yams, a food crop grown in the central and northern savannah. Dependence on rainwater for these crops correlates to coefficients of 0.88 for cocoa production and 0.75 for yams. In general, the long rainy season is decreasing, with recorded drops from six to four months. During half of the years in deficit, the water requirement of cocoa trees was not met during the long rainy season. This prolonged water stress resulted in the death of both young and adult plants, which in turn led to a decline in the production of butter from cocoa beans. In recent decades, yam production was also negatively affected by irregular rainfall. Among the farmers surveyed, about 55% marketed part of their production. However, they unanimously acknowledged that their incomes from yam production had not met their needs for years because few farmers earned more than Euros 152.

In Benin, corn is the main food crop in the South. In Couffo, the rainwater excess, especially in 2007–2008, caused loss of part of the corn harvest. In low-lying areas, some farmers lost all of their crops (Houssou-Goé 2008). In the Ouémé basin, cotton, groundnut, and sorghum are predicted to grow better with the reduction in the length of the cropping season forecast for the 2030 horizon. On the other hand, crops vulnerable to drought, like cassava, yam, corn, and rice, will be negatively impacted.

A modest decline in yield was observed for legumes (soya and bean) and sweet potatoes. Incomes across all crops declined.

In most parts of Burkina Faso, changes in early and late season, dry spells, heavy rains and pest and disease attacks affect farm productivity through physical damage to plants (Ouoba 2013). Indeed, in the case of a late or false start of the rainy season, there is poor growth and/or death of seedlings, the appearance of worms and caterpillars, termite attacks, etc. Heavy rains are equally devastating. Excessive rainfalls generally cause flooding, the uprooting of stems, the rotting of seeds (especially at the beginning of the season), asphyxia, and sometimes non-ripening of crops. Losses in agricultural production due to flooding of cultivated fields were estimated at Euros 2,748,727 in 1992 and Euros 97,474,891 in 1994 (MECV 2007). These factors, which lead to a decline in agricultural production, raise the crucial issue of food security. The drop-in rainfall also induces a drop-in millet yields, particularly in Dori in the Sahel. In the southern areas, corn yields fell sharply due to the July, August, and September water deficit (MECV 2007). In fact, corn is very sensitive to drought: the slightest shortage of rainfall can jeopardize the whole harvest.

In Senegal, too, the interannual variability of rainfall affects crops. A delay in the start of the rainy season and the annual rainfall deficit in 2014, for example, compromised the harvest of millet and groundnuts in Louga, Thiès, and Mbour (in the northwest of the country). Yield declines of 8–31% were recorded. In the center (Kaolack) and the south (Ziguinchor) of the country, where rain deficits were milder, yield decreases were less severe (Diop et al. 2016). From 1961 to 2013, yields fell significantly in Louga and Kébémer in the north-central area of the country (Sambou 2015). Even in areas where fields are irrigated, such as the Senegal River Valley and the Anambé Basin in Upper Casamance, the development of farming depends on rainwater, since its abundance or scarcity determines the availability of water resources and, therefore, yields. In the south (communities of Bona and Diacounda), in 2007, the production of millet and corn decreased, respectively, by 38% and 40% because of the rainfall deficit, compared to 2006 (Diédhiou 2008). Rice production also dropped by 20% in the same year. From 1981 to 2015, the year 2007 was noteworthy, with one of the shortest rainy seasons on record.

3.3.2 Impacts of Rainfall Variations on Pastoral Activities

Grazing prevails mainly in the Sahelian and Sudanian zones of the four countries, where the amount of rainfall and its effects vary significantly. These factors include late rainfalls, heavy rains, pockets of drought, early cessation of rains, and short rainy seasons. Late rainfalls result in water shortages and, therefore, less pasture area, as well as skin diseases and diarrhea in some animals, which often result in death. These effects are also observed when the rainy season is too short. In Senegal, for example, a reduction in the number of ponds compared to the pre-break period of 1968 is observed by farmers in the areas of Sakal and Ndande (in the northwest of the country). In contrast, increased precipitation favors milk production. The recent

increase in rainfall has allowed an increase in milk production, particularly between 2009 and 2010, with 2% more than the 2005–2010 average (Sambou 2015).

3.3.3 Impacts of Rainfall Variation on Inland Fisheries

With the reduction of volume and area of water bodies following unfavorable changes in climate parameters, production of inland fisheries has declined in the countries from which information is available. In Ivory Coast, fish production in Béoumi (on the left bank of Lake Kossou) decreased from 1,142 tons in 2009 to 320 tons in 2015, according to the Departmental Agency of the Ministry of Animal and Fish Production (MPAH 2016). This magnitude represents a threat to self-sufficiency and food security in that area. Burkina Faso, which has more than 200,000 hectares of surface water including rivers and ponds, and 1,450 dammed lakes and reservoirs that can be used for fishing and fish production in general (Bationo 2015), is similarly affected. Indeed, precipitation fluctuation, fill rate of water bodies, drying up of waterways, disappearance of certain species, and the opening of the flood evacuation valves that facilitates the migration of fish are factors that help explain decline in production. In Senegal, inland fish catches are estimated at 37,000 tons in 1999. This activity is practiced in both freshwater and brackish water (MPTM 2001). Fish farming has been integrated with rice production since the 1900s (Niane and Ndong 2015). The decline in inland fish catches is mainly due to droughts and changes in river flow rates. Dams, overexploitation, dilapidated pirogue fleets, fishing techniques, etc., are other disabling factors (MPTM 2001).

3.4 Adaptation Strategies

West African populations have been grappling with rainfall variability for a long time. As a consequence, people have developed strategies to find water in all seasons, regardless of precipitation volume and temporal distribution. These initiatives are now supported by states and international institutions.

In the Sahelian zone, water collection technologies are many. Farmers collect rainwater from roofs and channel spring water to reservoirs. In case of drought, stored water is used for about five months, depending on the capacity of the tank (Ajani et al. 2013). In vegetable gardens, water is stored in basins fed by PVC pipes connected to water pumps. This technique reduces water loss compared to irrigation canals (Nkwade et al. 2014). Water can also be stored in retention basins. In Bobo-Dioulasso, residents use pumps and increase the depth of wells to address a lack of water (Toe 2014). In Senegal, the deepening and cleaning out of wells ensure a continuous water supply (UICN 2011).

3.4.1 Changes in Crops and Varieties

Two main government departments provide technical guidance to farmers growing perennial and food crops in Ivory Coast. Firstly, the National Center for Agronomic Research (CNRA: Centre National de Recherche Agronomique) is remarkably effective in researching and implementing new plant varieties adapted to local climate requirements. This department, through its many research sites, innovates in crops and varieties. For example, in the cocoa sector, several varieties with improved resistance to rainfall and climate variations have emerged. Secondly, the National Rural Development Support Agency (ANADER: Agence Nationale d'Appui au Dévelopment Rural), another government department, provides support and expertise to the farming community on the ground, by offering new varieties of cocoa from the National Center for Agronomic Research (CNRA). These efforts support production with high yields by using climate-resistant crops. These new, improved varieties of cocoa are gradually replacing traditional varieties that have been grown in orchards over thirty years. The ANADER also trains farmers in agroforestry techniques and codes of conduct, and in the proper use of plant protection products to control pests and destructive diseases. For instance, cocoa pod mirids have a negative effect on yield and production. In a food crop sector like yams, both agencies are involved and help introduce early varieties.

In Benin, the choice of varieties and crops is decisive for harvests. Farmers use improved seed varieties to adapt food or market-garden production to climate change—for example, cowpea with four vegetative phases that correspond to variable water requirements. For this reason, farmers are increasingly using early varieties (*TVX-1850-01-F*) that require 65 days from planting to harvest and semi-late (*IT81D-1137*) varieties of 70–80 days, while gradually reducing the use of late varieties (*TN98-63*) of 90–100 days. Early varieties such as 75-day corn are grown in some areas to cope with the rainfall deficit. The same is true for the 90-day groundnut (*TS-32-1*), which is adopted instead of the 120-day groundnut (*69–101*). The early 75-day corn crop is grown in association with beans at the expense of 90-day corn crops for the sole purpose of overcoming constraints related to irregular and inadequate rainfall. Early varieties thus have the advantage of reaching their full development before the onset of floods or droughts. However, a major limitation of this approach remains the supply of seeds that doesn't meet demand.

In Burkina Faso, farmers are abandoning local varieties of cereal such as sorghum, millet, and corn. The new early varieties do not exceed 60 days to ripen. Creeping plants of the *Cucurbitaceae* family are also grown, supported by agricultural research institutes. The lowlands, which are used for rice-growing during the rainy season, are exploited for corn production or market gardening in the off-season (GWP 2010).

In Senegal, too, early varieties are preferred. The adoption and diversification of crop varieties, especially those developed by research institutes such as the Senegalese Institute for Agricultural Research (ISRA: Institut Sénégalais de Recherches Agricoles), allow farmers to better adapt to the shortening of rainy seasons and the recurrence of dry spells. Growing cowpeas (*Vigna unguiculata*) has become widespread in Senegal because of their quick growth ($\leq$60 days). *Souna* and *IBV*

8004 millet varieties ripen in 75 and 95 days, respectively. The *55-437* and *fleur-11* varieties of groundnut can complete their cycles in 90 days (MA 2012).

3.4.2 Changes in Farming Practices

In Ivory Coast, several changes in farming practices have been implemented because of irregular rainfall. We will consider two major events that resulted in changes in the cropping calendar and the reorientation of farming lands in the region of Bouaké in the heart of the savannah. New farming techniques, in addition to schedule modifications, have included staking fruit trees and mulching mounds. The farming calendar had usually begun in March with the clearing and removal of grass in new plots. This practice has become obsolete due to evolution of the temporal distribution of rainfall in the region. A one-month delay at the beginning of the rainy season has shifted this process from March to April. New agro-climatic conditions compel farmers to reorient toward increasingly colonized lowlands and to rice-growing and market gardening.

Farming changes have also been made in Benin in order to maintain good harvests. Crop association is a system that consists of growing on small farms with several crops in the same plot, generally in very fertile backyard gardens. This system allows farmers to diversify production and avoid repeated weeding. The crop associations most frequently encountered in the study area are shown in Table 2.

Crop association also responds to erosion caused by rainwater on fragile ferruginous soils. Moreover, it has the enormous advantage of achieving a significantly higher yield than for crops grown separately. In rural communities, this technique is used because different plants draw different nutrients from the soil, and some plant residues produce nutrients for other plants. In the event of a break in the rainy season, plants with low water requirements can still produce acceptable yields (Houndénou 1999) and in case of excessive rainfall, plants that demand water are more resistant. Crop association also optimizes a short rainy season. Other forms of adaptation being explored are the exploitation of lowlands, ridging, crop rotation—notably with yams, cotton, and cassava—and the abandonment of the empirical farming calendar that is no longer suitable to the changing climate.

Table 2 Crop associations in the Ouémé Watershed

Associated crops						
Yam + Millet	Yam + Sorghum	Yam + Corn	Yam + Bean	Yam + Okra + Chili	Corn + Millet	Corn + Sorghum
Corn + Beans	Sorghum + Groundnut	Corn + Groundnut + Cassava	Cassava + Sorghum	Cassava + Millet	Cassava + Millet + Beans	Cassava + Yam + Sorghum

Source Koudamiloro (2017)

In Burkina Faso, plowing reduces runoff by holding water in the soil. When the plants reach an advanced vegetative stage, ridging, with well-known techniques such as *zaï*, *demi-lune,* and mulching, allows the concentration of water in furrows. These techniques use stony barriers, bunds, micro-dams, lowland development, etc. (GWP 2010).

In Senegal, because of irregular precipitation, especially pronounced from 1968 to 1998, farmers, on their own initiative or with the support of non-governmental organizations, have developed strategies through crop diversification and conversion to other economic sectors. Farmers are unable to accurately assess the effects of precipitation until August, when it is too late to sow on the plateau, so they generally take advantage of the opportunities offered by the topography of their respective environments, and develop practices that respond to the topo-sequence and the amount of time ponds remain in different segments of the slope. Thus, lowland areas are exploited with rice varieties adapted to the limited amount of water available in short rainy seasons, which clears the banks while exposing rice-growing valleys to silting. Moreover, the development of market gardening in rural areas, especially in the dry season, indicates the awareness of farming communities to climate hazards.

3.4.3 Crop Insurance as a Response to Changes in Rainfall

Climate insurance works by taking into account the level from which bad climatic conditions start to negatively impact plants, known as the **trigger threshold**, and

Table 3 Range of index insurance products in Ivory Coast, Burkina Faso, and Senegal

Countries	Crops	Covered risks	Input data	Precision
Ivory Coast	Corn	Drop-in production	Vegetation, NDVI*, Satellite Emodis	5 km × 5 km
Burkina Faso	Multi-cereal*	Water deficit (3 phases)	Climate, Rainfall-estimate Satellite NOAA ARC 2	10 km × 10 km
Senegal	– Groundnut – Corn – Millet – Rain-fed rice	– Sowing failure – Water deficit (3 phases) – Dry spells	Climate, Anacim's* weather stations, automatic and mechanical	5-to-7-km radius of the rain-gauge
	Multi-cereal	Water deficit (2 phases)	Climate, Rainfall-estimate Satellite NOAA ARC 2	10 km × 10 km

(Kara and Weber 2017)
* Multi-cereal: several cereals
* ANACIM: National Agency of Civil Aviation and Meteorology (Senegal)
* NDVI: Normalized Difference Vegetation Index

the level at which climatic conditions are intolerable for plants, when they enter a state of total water stress, known as the **exit threshold** (Shadreck et al. 2017). These two thresholds are generally observed during different growing phases of crops in the rainy season. When the trigger threshold is reached, minimum insurance compensation is paid. The amount increases progressively to a maximum of 100% when the meteorological status corresponds to the exit threshold.

Index climate insurance was introduced in 2011 in Ivory Coast, Burkina Faso, and Senegal. In Benin, it existed from 2013 to 2015. Covered risks are generally limited to sowing failure and lack of water during the different growing phases: vegetative, flowering, and ripening. Two other phases can also be covered, either the beginning or/and the end of the cropping season, as is the case with the satellite index (Table 3).

Between 2011 and 2017, payouts varied from one year to another depending on weather conditions. The year with the most payouts was 2014 (Table 4).

Table 4 Index insurance statistics between 2011 and 2017 (PlaNet Guarantee)

Ivory Coast								
Years	2011	2012	2013	2014	2015	2016	2017	Total
Insured farmers						242	850	1092
Premiums (Euros)						5 999	20 238	260236
Claims (Euros)						2 723	–	2 723
Claims ratio	45% (end 2016)							
Benin								
Years	2011	2012	2013	2014	2015	2016	2017	Total
Insured farmers			48	1 099	1 200			2 347
Premiums (Euros)			812	10 178	11 113			22 103
Claims (Euros)			811,8	6 879				7 691
Claims ratio	35% (end 2015)							
Burkina Faso								
Years	2011	2012	2013	2014	2015	2016	2017	Total
Insured farmers	194	1 340	2 332	8 298	5 565	7 476	4 080	29 091
Premiums (Euros)	3 615	16 859	55 615	95 684	48 714	36 104	25 282	278 256
Claims (Euros)		17 059	20 262	88 116	54 202	7 414	–	187 053
Claims ratio	74% (end 2016)							
Senegal								
Years	2011	2012	2013	2014	2015	2016	2017	Total
Insured farmers		60	2 326	5 660	8 962	12 957	14 247	44 212
Premiums (Euros)		1 615	43 170	92 031	189 496	294 581	337 445	958 339
Claims (Euros)		0	23 122	68 334	71 651	114 738	–	277 844
Claims ratio	45% (end 2016)							

"–" means no data available

In Benin, insurance appears to be the most effective tool for sustainable risk management in farming. Indeed, the purpose of managing farming-related risk is to ensure the sustainability of farms while reducing their exposure to risk and supporting farmers who are coping with exceptional disaster. It involves defining levels of risk exposure and corresponding degrees of coverage. The Mutual Crop Insurance of Benin (AMAB: Assurance Mutuelle Agricole du Bénin) is the multi-risk crop insurance syndicate established in that country. The main crops covered are corn, cashews, cotton, cassava, groundnuts, cowpeas, and yams. To participate, farmers must first subscribe to a multi-risk crop insurance policy after completing simple membership formalities and payment of a premium of Euros 12 for six months of coverage. However, farmers surveyed indicate that improvements are needed to optimize the operation of the AMAB.

3.4.4 Adaptation of Breeders

In Ivory Coast, to alleviate the effects of climate change, cattle farmers in the region of Boundiali, in the north of the country, changed the raising of livestock by strengthening the feed system with crop byproducts. This resulted in the evolution of a breeding system from purely nomadic to increasing adoption of transhumance (cycling livestock between highlands and lowlands seasonally). To boost the development of pastoral activity in Boundiali, for example, government departments (the former SODEPRA and ANADER) built agro-pastoral dams on both sides of the territory of Boundiali. But exposure to eutrophication and lack of maintenance have rendered most of these dams unusable today. The livestock manager at the regional branch of ANADER in Boundiali reports that some of them are drying up.

In Benin, strategies developed by herdsmen to adapt to climate crises and the effects on their livelihoods are transhumance, use of legume straw for cattle feed, sharing drinkable water with livestock, and unlawful invasion of protected areas.

In Burkina Faso, transhumance, previously unknown in some areas, has become a widespread practice with rainfall variability. Villages have been built in transhumance corridors—evidence of the colonization of these areas by herders. The lack of grazing land has compelled farmers to practice semi-intensive farming and to store fodder. Herds are being recomposed, with hardy species (goats, donkeys, and camels) supplanting cattle and sheep. Herders also tend to sell part of their herds during the dry years to buy food and increase the chance of survival of their remaining animals (GWP 2010).

In Senegal, an early warning system had been set up in partnership with the Ecological Monitoring Center (CSE: Centre de Suivi Ecologique), based on regional agro-meteorologic and hydrologic data. In the Ferlo (northern Senegal), climate information warns farmers of the lack of pasture or ponds to prevent herd mortality. Alerts are broadcast through community radios, weekly markets, and on the Internet. A bushfire alert system was tested using mobile phone messaging. To prevent conflict with farmers, information on the location of potentially relevant events along pastoral corridors is provided systematically (Martin 2015). Climate constraints,

which impose challenges to pastoral activity and the social practices associated with them, are compelling pastoral communities and public authorities to increasingly develop better coping strategies. A focus on ponds, especially in this part of the Sahel, has been and remains an effective albeit partial response to the difficulties of pastoral livelihoods, which are to a large extent impacted by climate variability. In addition, the migration to cities, once regarded as the preserve of farmers, now appears to be a survival strategy for pastoral communities.

3.4.5 Adaptation of Inland Fisheries

In Ivory Coast, as fishermen are losing their livelihoods because of climate change impacting their sector, some have opted for alternation and others have left the sector for other livelihoods altogether. Surveys reveal that in 2016, 73% of fishermen have opted for alternative livehoods to fishing, including farming, such as market gardening. Of those who have abandoned fishing, most are Gôdè aboriginals; the majority of Bozo Malian fishermen have remained in the fishing sector. Our surveys found, however, that 27% of Bozo Malian fishermen have completely converted to another activity. Cashews remain the most popular crop; former fishermen indicate that cashew farming is attractive because the natural environment is conducive to successful cashew production, which generates high incomes.

In Benin, fishermen have developed different strategies to resist the effects of climate change, including deepening of ponds, use of appropriate fishing equipment, prohibition of the use of pesticides in waterways, and the protection of ponds and other water bodies by ceasing all fishing activity there to allow for restoration of the fish population. Fishermen report that deepening ponds increases the amount of water and reduces the rise in water temperature. The use of appropriate fishing equipment is also a strategy to address the effects of climate change on fish production. Fishermen report that prohibition of fine mesh nets promotes sustainable exploitation of ponds, but the ban has been only modestly effective, with 60% of fishermen continuing to use these nets despite their destruction of aquatic biodiversity.

In Senegal, to address declining fish catches, fishermen convert temporarily or permanently to farm work with the development of modern farming and rice growing in northern Senegal (MPTM 2001). The first trials of aquaculture, to mitigate the effects of lower catch volumes, were conducted in the 1980s in the Senegal River Valley (Niane and Ndong 2015). Aquaculture has proved to help mitigate climate vagaries, affecting rivers, lakes, and other water bodies, and is now well-established in Senegal. Among its objectives established in 2001, the Ministry of Fisheries and Maritime Transportation has created a Fisheries and Aquaculture Institute at Cheikh Anta Diop University in Dakar. The Ministry is making plans to share experience in aquaculture with countries including Mali, Ivory Coast, and Burkina Faso. It also hopes to develop a partnership with the FAO through regular participation in the activities of the Committee for Continental Fisheries and Aquaculture (CCFA).

4 Conclusion

Several methods have allowed analysis of trends in climatic evolution in Ivory Coast, Benin, Burkina Faso, and Senegal. The decrease in rainfall corresponds to that of total availability of water. Although the Sahel has gone through spells of drought, wet periods have also been documented. Similarly, parts of the Sudanian and Guinean climate zones have experienced rainfall breaks during different time series. The inclusion of recent changes in longer periods of climate change in the Sahelian, Sudanian, and Guinean zones of West Africa has mitigated their exceptional character. In contrast, climate and hydrologic models from the IPCC predict increases or decreases for the coming decades, until 2100. Thus, even if there were a likelihood of rainfall increase in the Sahel in the 1990s and 2000s, West Africa remains subject to elusive climate variability. The 2014 deficit, in a context of relatively improved precipitation, has shown that any reactive strategy based on models, or even findings based on global averages, may prove unreliable. We must act and think locally, and now.

Crops such as yams in Ivory Coast and Benin, as well as inland fisheries, show that countries with abundant rainfall not only remain vulnerable to rainfall deficits, but are also susceptible to floods. Cross-sectoral mobility and strategies independent of climate are, therefore, necessary for effective adaptation. Climate information must, therefore, be associated with seasonal migrations and the development of alternative activities (agroforestry, solar energy production, ecotourism, etc.). Variety maps must offer a plurality of varieties for a given location so that farmers can use the most appropriate crop or variety for any given growing season. Water sobriety is a relevant alternative to manage water resources. Since most of the loss of irrigation water is through evaporation and infiltration, increasing available water resources may allow for the exploitation of more land.

The management of water resources in West Africa faces the challenges of spatial and temporal distribution. Crop insurance can mitigate the effects of unequal distribution by financially offsetting difficult periods and deprived climatic regions.

Transboundary rivers are natural systems of water distribution in West Africa. Analyses indicate that in the region's water tower (the Fouta Djallon Mountains), only slight variations in rainfall and runoff are recorded, compared to the rest of the region. Despite the effort to exploit water resources of transboundary rivers, political and financial obstacles have interfered with exploiting the full potential of those rivers. People living in areas located more than one kilometer away from waterways prefer to use groundwater, which is now easier to access by drilling and pumping (solar energy is used in some areas in Senegal).

Climate change patterns in West Africa demonstrate the crucial importance of hydrological potential (both surface water and groundwater), despite multiple signals and warnings. The effective management of water resources improves many opportunities in farming, and also in inland fishing. In addition, it helps restore the population balance between deserted places and overpopulated capital cities. The climate context of West Africa reveals previously unknown facts about the relationship among

climate, water, and society. Population growth, constant demand for water in cities and factories, and changes in lifestyle are all factors that increasingly affect water resources.

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