UNIVERSITI PUTRA MALAYSIA

MODELLING THE IMPACTS OF CLIMATE CHANGE ON HYDROLOGY AND WATER RESOURCES IN THE NIGER-SOUTH SUB-CATCHMENT OF THE NIGER RIVER BASIN, NIGERIA

OLORUNTADE, AJAYI JOHNSON

MODELLING THE IMPACTS OF CLIMATE CHANGE ON HYDROLOGY AND WATER RESOURCES IN THE NIGER-SOUTH SUB-CATCHMENT OF THE NIGER RIVER BASIN, NIGERIA

By

OLORUNTADE, AJAYI JOHNSON

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfillment of the Requirements for the Degree of Doctor of Philosophy

March 2017

DEDICATION

This thesis is dedicated to my children:

Benedict Bolade, Olabanji Opemiposi and Morolayo Abigail

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfillment of the requirement for the Degree of Doctor of Philosophy

MODELLING THE IMPACTS OF CLIMATE CHANGE ON HYDROLOGY AND WATER RESOURCES IN THE NIGER-SOUTH SUB-CATCHMENT OF THE NIGER RIVER BASIN, NIGERIA

By

OLORUNTADE, AJAYI JOHNSON

March 2017

Chairman : Professor Thamer Ahmad Mohammad, PhD
Faculty : Engineering

The Niger River Basin (NRB), located between latitudes 4–7.5° N and longitudes 4.5–7° E, is a trans-boundary basin which transverses about nine countries of West and Central Africa with a total active area of about 925,796 km^2, of which about 60% is an agricultural rain-fed and irrigated area. In addition, various hydropower stations are currently in operation along the course of the main river. Hence, there is a growing concern that any unfavourable climate change impact in the basin might have consequential impacts on the socioeconomic lives of the people of the country.

To assess these possible impacts of future climate change on the water resources in the NRB, a sub-catchment of the Nigerian part, hereafter referred to as Niger-South Basin (NSB) is chosen in the present study. Statistical, trend and drought analyses were performed on some hydro-climatic variables to ascertain the direction of change in climate and as well the occurrence of drought with a view to evaluating the likely impacts on hydrology and water resources in the basin. The results showed a relatively uniform increase in warming and drying over the entire landscape (1948-2008). While the decade 2000s and year 1983 were the driest, average annual rainfall was dominated by August (15%), with the summer season (June, July and August; JJA) also contributing the highest (40%). Although, only 15% was significant ($\alpha < 0.1$), rainfall trend was generally negative, with about 8 months exhibiting downward trend, while only JJA showed significant upward trend.

Similarly, warming over the basin was relatively uniform; while the period between 1978 and 1979, and year 1998 were the warmest (mean temperature = 27.8 °C), the warmest season was in spring (March, April and May). Significant increasing trends were observed for all series (minimum; TMIN, maximum; TMAX and mean temperature; TMEAN) and on monthly, seasonal and annual bases, but trends were strongest in TMIN and in autumn. However, average warming over the entire

landscape was 0.83 ^{o}C per annum. Drought analysis indicated pockets of wet and dry conditions of varied severities since 1970, with meteorological droughts observed during 1973 to 1977 and 1982-1984, while the decade 1980s showed between moderate and extreme droughts. Increased warming influenced hydrological drought, especially during the 1990s, given the relatively higher correlation between the Standardised Precipitation Evapotranspiration Index (SPEI) and the Standardised Runoff Index (SRI), while a strong 2-year periodic power was found during the late 1970s and early 1980 controlling drought. Although a moderately wet basin has been observed, with increased warming, a reversal of the situation might be experienced in the future.

For the hydrological modelling, a hydrological model, Soil and Water Assessment Tool (SWAT) was set up to evaluate the impacts of the likely future climate change on the hydrology and water resources in the NSB. Calibration and validation of the model was done using the discharge data for the period 1980-1989 and 1990-1999, respectively. With Nash-Sutcliffe (NS) of 0.82 (calibration) and 0.73 (validation), the model indicated good performance and robustness. Thereafter, five bias-corrected General Circulation Models (GCMs) (CNRM, GFDL, CCCma, ICHEC and NCC) were downscaled and used to drive the model for the future (2040-2059 and 2070-2089) hydrological parameters simulations. The results showed declines in average annual precipitation, runoff, baseflow, streamflow and potential evapotranspiration (PET) of about 16%, 65%, 2%, 23% and 1.7%, respectively during the mid-century (2040-2059), and 14%, 60%, 0.3%, 20% and 0.8% for precipitation, runoff, baseflow, streamflow and PET during the late-century (2070-2089). Notwithstanding the uncertainty observed during the study, the results showed that the basin is highly sensitive to climate change. Therefore, adoption of good water resources management and adaptation strategies are needed to ensure sustainable water supply in the basin especially during the mid-century.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk Ijazah Doktor Falsafah.

MEMODEL IMPAK PERUBAHAN IKLIM KE ATAS HIDROLOGI DAN SUMBER AIR DI TADAHAN KECIL NIGER SELATAN DALAM LEMBANGAN SUNGAI NIGER, NIGERIA

Oleh

OLORUNTADE, AJAYI JOHNSON

Mac 2017

Pengerusi : Profesor Thamer Ahmad Mohammad, PhD
Fakulti : Kejuruteraan

Niger River Basin (NRB), atau Lembangan Sungai Niger yang terletak di antara latitud 4–7.5^0 N dan longitud 4.5– 7^0 E, adalah sebuah lembangan sungai merentas-sempadan yang merentas sembilan buah negara Afrika Tengah dan Barat dengan keluasan aktif berjumlah 925,796 km^2, di mana kira-kira 60% adalah kawasan pertanian yang sering dilanda hujan dan berpengairan. Tambahan pula, pelbagai stesyen kuasa hidro kini sedang beroperasi di sepanjang sungai utama. Oleh itu, terdapat satu kebimbangan bahawa apa sahaja impak perubahan iklim yang tidak diingini di lembangan sungai ini boleh memberi kesan ke atas kehidupan sosio-ekonomi rakyat negara ini.

Untuk menilai impak yang mungkin berlaku daripada perubahan iklim masa depan, ke atas sumber air di NRB, satu tadahan air kecil di sebelah Nigeria, yang dipanggil Niger-South Basin (NSB) atau Lembangan Selatan Nigeria telah dipilih dalam kajian ini. Analisis statistik, trend dan analisis kemarau telah dijalankan ke atas beberapa pembolehubah hidro-iklim untuk menentukan arah perubahan iklim dan begitu juga dengan kejadian kemarau untuk menilai impak-impak berkemungkinan ke atas sumber hidrologi dan air di lembangan sungai tersebut. Keputusan menunjukkan bahawa terdapat satu peningkatan seragam dalam pemanasan dan pengeringan ke atas keseluruhan landskap (1948-2008). Walaupun dekad tahun 2000 dan tahun 1983 adalah yang terkering, purata taburan hujan tahunan didominasi dalam bulan Ogos (15%), dengan musim panas (June, July and August; JJA) juga menyumbang sebagai yang tertinggi (40%). Walaupun hanya 15% yang dikira signifikan ($\alpha < 0.1$), tren taburan hujan secara umumnya adalah negatif, dengan kira-kira 8 bulan menunjukkan tren menurun, sementara hanya JJA menunjukkan tren menaik yang signifikan.

Begitu juga dengan pemanasan lembangan sungai yang seragam; tempoh di antara tahun 1978 dan 1979, dan tahun 1998 adalah yang terpanas (min suhu = 27.8 ^{o}C), musim terpanas ialah musim bunga (March, April dan May). Tren menaik yang signifikan diperhatikan untuk semua siri (minima; TMIN, maksima; TMAX dan min suhu; TMEAN) mengikut kiraan bulanan, musim dan tahunan, tetapi tren paling kuat ialah TMIN dan dalam musim luruh. Namun demikian, purata pemanasan ke atas seluruh landskap ialah 0.83 ^{o}C setahun. Analisis kemarau menunjukkan beberapa keadaan basah dan kering dengan keseriusan yang berbeza sejak tahun 1970, dengan kemarau meteorologi diperhatikan dalam tahun 1973 sehingga 1977 dan 1982-1984, sementara dekad ke 1980an menunjukkan kemarau yang sederhana dan ekstrim. Pemanasan yang semakin meningkat mempengaruhi kemarau hidrologi, terutamanya dalam tahun 1990an, berdasarkan kepada korelasi lebih tinggi di antara *Standardised Precipitation Evapotranspiration Index* (SPEI) atau Indeks Evapotranspirasi Hujan Piawai dan *Standardised Runoff Index* (SRI) atau Indeks Larian Air Piawai, sementara satu kuasa berkala 2-tahun yang dijumpai pada lewat tahun 1970an dan awal tahun 1980 mampu mengawal kemarau. Walaupun diperhatikan bahawa lembangan sungai itu agak basah, dengan pemanasan yang semakin meningkat, situasi yang bertentangan pula yang akan dialami pada masa akan datang.

Untuk pemodelan hidrologi, satu model hidrologi, *Soil and Water Assessment Tool* (SWAT) atau Alat Penilaian Tanah dan Air telah digunakan untuk menilai impak perubahan iklim yang mungkin akan berlaku pada masa akan datang ke atas sumber hidrologi dan air di NSB. Kalibrasi dan pengesahan model dibuat menggunakan data discaj untuk tempoh 1980-1989 dan 1990-1999, masing-masing. Dengan Nash-Sutcliffe (NS) 0.82 (kalibrasi) dan 0.73 (pengesahan), model itu menunjukkan prestasi dan kekuatan yang baik. Seterusnya, lima model Pengaliran Umum yang telah diperbaiki biasnya atau *General Circulation Models* (GCMs) (CNRM, GFDL, CCCma, ICHEC dan NCC) telah direndah-skalakan dan digunakan untuk memacu model ini untuk simulasi parameter hidrologi masa hadapan (2040-2059 and 2070-2089). Keputusan menunjukkan penurunan dalam purata hujan tahunan, larian air, dasar aliran, dasar sungai dan evapotranspirasi (PET) dalam anggaran 16%, 65%, 2%, 23% dan 1.7%, masing-masing pada pertengahan abad (2040-2059), dan 14%, 60%, 0.3%, 20% dan 0.8% untuk hujan, larian air, dasar aliran, dasar sungai dan PET lewat abad ke (2070-2089). Walaupun terbit rasa ketidakpastian dalam kajian ini, keputusan menunjukkan bahawa lembangan sungai sangat sensitif kepada perubahan iklim. Oleh itu, penggunaan pengurusan sumber air yang baik dan strategi adaptasi diperlukan untuk memastikan bekalan air terus mampan di lembangan sungai ini terutama dalam abad pertengahan ini.

ACKNOWLEDGEMENTS

I give glory to God Almighty for His kindness to me always without whom I would have been unable to do anything. I wish to immensely appreciate the efforts of the Chairman and members of my Supervisory Committee - Professor Thamer Ahmad Mohammad, Assoc. Professor Abdul Halim bin Ghazali and Dr. Aimrun Wayayok, for their supports. Equally worthy of mention is the encouragement received from Professor Lee Teang Shui who was the first Chairman of my Committee, but left due to his retirement from the University.

Of very important is the contribution of Professor P. G. Oguntunde whom I owe a lot of gratitude for the eventual completion of this work. He has remained my pillar of support even when it was almost impossible for me to move forward. Thank God, his kindness is being rewarded by the Almighty and this I pray will continue in Jesus name. I also wish to acknowledge the support of his friend and my host at the University of Cape Town, Dr. B. J. Abiodun for his ceaseless words of encouragement and numerous assistances in data sourcing. So also are the supports of Professor Gunnar Lischeid and Dr. Ottfried Dietrich, both of the Institute of Landscape Hydrology, Leibniz Centre for Agricultural Landscape Research (ZALF), Muencheberg, Germany, for hosting me during my short training in SWAT.

Similarly, three families stood out in their support for this work and I cannot but appreciate them; they are the families of Elder and Mrs. M. S. Ayeerun, Mr. and Mrs. M. O. O. Idowu and Mr. and Mrs. G. A. Akadiri. Their love for my progress really helped in keeping me going. I also appreciate the ceaseless brotherly love and supports of Dr. G. B. Iwasokun, who have been a good role model to me. Equally important is the support of my student-colleagues and friends, Dr. Peter Aderemi Adeoye, Mr. Segun Emmanuel Adebayo and Engr. O. S. Sajo. In addition, I like to appreciate the prayers of those Pastors who have supported me in this journey as well as the entire Congregation, Christ the Rock of Salvation Church, Sabo, Ugbe Akoko, Nigeria. I thank all my friends and relatives who have always believed in me and for their supports during the course of the programme.

I sincerely appreciate the Management of Rufus Giwa Polytechnic, Owo, for granting me the study leave under which this study was undertaken and the Tertiary Education Trust Fund (TETFUND) for the Scholarship used in pursuing the programme. My present and past H.O.Ds and colleagues at the Department of Agricultural and Bio-Environmental Engineering Technology, Rufus Giwa Polytechnic, Owo are all appreciated. The assistance of my very senior colleague and friend, Engr. Mogaji, K. O. is worthy to be mentioned and appreciated.

Knowing that Adam could not achieve much alone, God created Eve! Thus, to my wife, Mrs Bosede Eunice Oloruntade and children, I say thank you indeed for keeping the home during my long period of absence. And to my mother, I wish you long life so that you could reap the fruit of your good work.

Thank you all!

I certify that a Thesis Examination Committee has met on 10 March 2017 to conduct the final examination of Oloruntade Ajayi Johnson on his thesis entitled "Modelling the Impacts of Climate Change on Hydrology and Water Resources in the Niger-South Sub-Catchment of the Niger River Basin, Nigeria" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Doctor of Philosophy.

Members of the Thesis Examination Committee were as follows:

Badronnisa binti Yusuf, PhD
Senior Lecturer
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

Desa bin Ahmad, PhD
Professor Ir.
Faculty of Engineering
Universiti Putra Malaysia
(Internal Examiner)

Samsuzana binti Abd Aziz, PhD
Senior Lecturer
Faculty of Engineering
Universiti Putra Malaysia
(Internal Examiner)

Madan Kumar Jha, PhD
Professor
Indian Institute of Technology
India
(External Examiner)

NOR AINI AB. SHUKOR, PhD
Professor and Deputy Dean
School of Graduate Studies
Universiti Putra Malaysia

Date: 28 April 2017

This thesis was submitted to the Senate of the Universiti Putra Malaysia and has been accepted as fulfillment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

Thamer Ahmad Mohammad, PhD
Professor
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

Abdul Halim bin Ghazali, PhD
Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Member)

Aimrun Wayayok, PhD
Senior Lecturer
Faculty of Engineering
Universiti Putra Malaysia
(Member)

ROBIAH BINTI YUNUS, PHD
Professor and Dean
School of Graduate Studies
Universiti Putra Malaysia

Date:

Declaration by graduate student

I hereby confirm that:

- this thesis is my original work;
- quotations, illustrations and citations have been duly referenced;
- this thesis has not been submitted previously or concurrently for any other degree at any institutions;
- intellectual property from the thesis and copyright of thesis are fully-owned by Universiti Putra Malaysia, as according to the Universiti Putra Malaysia (Research) Rules 2012;
- written permission must be obtained from supervisor and the office of Deputy Vice-Chancellor (Research and innovation) before thesis is published (in the form of written, printed or in electronic form) including books, journals, modules, proceedings, popular writings, seminar papers, manuscripts, posters, reports, lecture notes, learning modules or any other materials as stated in the Universiti Putra Malaysia (Research) Rules 2012;
- there is no plagiarism or data falsification/fabrication in the thesis, and scholarly integrity is upheld as according to the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) and the Universiti Putra Malaysia (Research) Rules 2012. The thesis has undergone plagiarism detection software

Signature: ________________________________ Date: ________________

Name and Matric No: Oloruntade, Ajayi Johnson , GS33213

Declaration by Members of Supervisory Committee

This is to confirm that:

- the research conducted and the writing of this thesis was under our supervision;
- supervision responsibilities as stated in the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) were adhered to.

Signature: ____

Name of Chairman of Supervisory Committee: Professor Dr. Thamer Ahmad Mohammad

Signature: ____

Name of Member of Supervisory Committee: Associate Professor Dr. Abdul Halim bin Ghazali

Signature: ____

Name of Member of Supervisory Committee: Dr. Aimrun Wayayok

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

AR4	Fourth Assessment Report
CCCma	Met Office Hadley Centre, UK
CMIP5	Coupled Model Intercomparison Project 5
CN	Curve Number
CNRM	National Centre for Meteorological Research, France
CORDEX	Coordinated Regional Downscaling Experiment
CRU	Climate Research Unit, University of East Anglia, UK
DEM	Digital Elevation Model
DS	Descriptive Statistics
EDA	Exploratory Data Analysis
GCM	General Circulation Model
GFDL	Geophysical Fluid Dynamics Laboratory
GHG	Greenhouse Gases
GIS	Geographical Information Systems
HRU	Hydrologic Response Unit
ICHEC	Irish Centre for High-End Computing, Ireland
IPCC	Intergovernmental Panel on Climate Change
ISRIC	International Soil Resource and Information Center
ITCZ	Inter-Tropical Convergence Zone
LSR	Least Square Regression
M-K	Mann-Kendall
NASA	National Aeronautics and Space Administration, United States
NCC	Norwegian Climate Centre, Norway
NBS	National Bureau of Statistics, Nigeria

NRB	Niger River Basin
NRCS	Natural Resource Conservation Service, United States
NSB	Niger-South Basin
RCM	Regional Climate Models
RCP	Representative Concentration Pathways
SCS	Soil Conservation Service
SPEI	Standardised Precipitation Evapotranspiration Index
SPI	Standardised Precipitation Index
SRES	Special Report on Emission Scenarios
SRI	Standardised Runoff Index
SRTM	Shuttle Radar Topography Mission
SWAT	Soil and Water Assessment Tool
UNFCCC	United Nations Framework Convention on Climate Change
WA	West Africa
WRCP	World Climate Research Programme

CHAPTER ONE

INTRODUCTION

1.1 Background

Toward the end of the last century, the attention of the entire world and most especially researchers was shifted to the phenomenon of climate change. The change of climate is generally being attributed to the general warming of the earth as a result of increasing concentration of greenhouse gases (GHG) in the atmosphere. The Intergovernmental Panel on Climate Change (IPCC, 2007) defined climate change as any change in the state of climate that is identifiable (e.g. using statistical tests) by changes in the mean and/or the variability of its properties and that continues for a prolonged period, usually decades or longer. Climate change may also be defined as any change in climate over a period of time, either due to natural variability or as a result of human activity. In recent years, occurrence of climate change has been proved by rising surface temperatures, increases in atmospheric carbon dioxide concentrations and more extreme precipitation events (IPCC, 2013; 2007; 2001), with mostly concomitant negative socio-economic and environmental impacts. Generally, the impacts of climate change on regional basis could include increased frequency and magnitude of droughts and floods, and long-term changes in average renewable water supplies caused by changes in precipitation, temperature, humidity, wind intensity, duration of accumulated snowpack, nature and extent of vegetation, soil moisture, and runoff (Christensen et. al., 2007).

However, while the impacts of climate change are global, its effects are expected to be regional. There is a common consensus that developing nations, such as those in Africa, are more expected to be affected by the global impacts of anthropogenic GHG emissions because of their poor adaptive capabilities occasioned by lack of technical knowhow and poverty (Callaway, 2004; IPCC, 2007). The United Nations Framework Convention on Climate Change (UNFCCC, 2007) further observed that regions of the world that are least culpable for climate change are the most susceptible to the projected climate change impacts. For instance, whereas the African region contributes less to global warming because of the general low level of industrialization, warming is likely to be larger than the global annual average over the continent (Christensen et. al., 2007).

Moreover, there is an agreement amongst climate models on the increased warming that ranges between +2 ºC and +6 ºC especially in West Africa (WA) towards 2100 (Christensen et al., 2007). On the other hand, while there is no agreement amongst models as regards the direction of the future evolution of precipitation, about half of them predict increased rainfall and the other half decrease (Berg et al., 2013; Vigaud et al., 2011). Nonetheless, it has been argued that changes ranging from about −20 to +20% in annual rainfalls are capable of causing certain imbalance in the hydrological regime and water resources in the WA sub-region (Sultan et al., 2013).

As key components of the hydrological cycle, any changes in climate that affect rainfall and temperature will have proportionate impacts on the hydrological system of an area especially at the basin scale. For example, anthropogenic climate change is projected to intensify the hydrological cycle and therefore, leads to altered river flow systems in several parts of the world (Huntington, 2006). Bates et al. (2008) stated that changes in climate will fast-track the global hydrologic cycle with a rise in the surface temperature, changes in precipitation patterns and evapotranspiration rates. This will further affect soil moisture requirements and the physical structure of the vegetation canopy which play important roles in the hydrological system of a drainage basin. Consequently, the quantity, quality, timing and spatial distribution of water available in a basin to satisfy the many demands of societies are all affected. Moreover, the amount and strength of extreme hydrological events such as high flows and deep droughts may increase considerably in the future in line with climate change projections. Hannaford (2015) averred that climate change could have some of the most profound impacts on the society, due to increases in flood risk, decreases in water availability and degradation of water quality and ecosystem services through altered river flow regimes. As if confirming the foregoing, the Nigerian catchment of the Niger River Basin (NRB) has been experiencing annual flooding of great magnitude with devastating economic losses recently (Okpara et al., 2013).

Moreover, climate change which exerts instability on the availability of water especially in basins will also throw up serious challenges to water resources planning and management. Given that many water resources management structures are designed based on the average figure of hydro-meteorological variables, changes in their extremes could render planning and management strategies ineffective and inadequate. In this regard, water managers and planners will also face a herculean task at ensuring that future water demands are met even in the face of considerable uncertainties. Oguntunde et al. (2006) observed that climate change poses important consequences on regional and global water resources management and conservation. Therefore, water resources management task could become even more complex when dealing with a shared water basin such as the NRB where water users at the lower basin reach are usually at the mercy of the favourable disposition of those at the upper reach. This situation could be further worsened by the possible construction of large dams along the river channel in future by various countries sharing the NRB. Thus, given this scenario, ensuring sustainability of water will require adequate scientific understanding of the interaction of the water cycle, ecosystems, and other related issues under a changing climate.

The NRB is an important trans-boundary river basin which transverses about nine countries of West and Central Africa. It is of great socio-economic importance to about 100 million people living in the basin because many of their economic activities depend on water availability (Ogilvie et al., 2010). For example, agricultural production including fishing which employs over 60% of the people of the area relies on irrigation water supply from the basin. In addition, the Niger River is the main source of water supply for industrial and municipal uses for the people through the construction of reservoirs at several points. Furthermore, a greater percentage of electricity supply in some of the countries in the basin is through hydropower generation made possible by the dams constructed along the river valleys at different points. As at the last count, over 260 dams of different sizes were said to have been constructed in the basin to achieve the aforementioned purposes (Lienou, 2013). The river also provides opportunities for transportation across and within the countries especially during the period of high flows. However, despite its importance, recent reports have shown that the basin is drying out and experiencing low flow especially within the Nigerian catchment due to climate change and poor management (Olomoda, 2012; Sherbinin et al., 2013).

The Nigerian portion of the NRB which is of more interest in the present study is an important catchment of the basin. Apart from the construction of hydro-power dams along the basin at some points, it also serves as a source of water for agricultural, industrial and domestic uses at various levels. Ogilvie et al. (2010) reported that there is strong correlation between several human development variables and climate change in West African countries. Such a relationship which also applies within the NRB, involves underlying causal links between water and poverty. Moreover, as mentioned earlier, studies on WA climate have shown significant decrease in both rainfall amount and duration of the rainy season. Nevertheless, in Nigeria, intermittent floods (Figure 1.1) and drought have been the major features of climate change impacts. Thus, there is no debating the fact that the hydrology and water resources of the NRB is already being impacted by climate change, however, to what extent the impacts would be with regards to quantity and quality and the anticipated challenges of water resources management, call for investigation.

Figure 1.1 : Flood events in the Lower Niger River Basin, Nigeria due to climate change and variability (Source: Okpara et al. (2013))

1.2 Research Problem

Climate change is projected to have serious impacts on the timing and quantity of rainfall and runoff regimes in WA, including Nigeria, thereby threatening water resources availability for agricultural, industrial and domestic purposes. In addition, increasing frequency of floods in the country that have caused loss of human lives and croplands has been blamed on climate change. Presently, there is no adequate information with respect to the direction of change in climatic variables to allow for planning. Unfortunately, most studies on climate change in Nigeria and particularly in the present study area have been more of qualitative than quantitative, thereby lacking the ability to predict the future impacts of climate change on water resources availability. Moreover, there is lack of agreement amongst climate models on the direction of change in climatic variables over WA, especially rainfall, thus making projections, planning and water resources management for agriculture difficult. Meanwhile, alleviating poverty under the Sustainable Development Goals (SDGs) programme in the country will require adequate water resources planning and management for increased agricultural productivity.

Hence, the present study is conceived to proffer solutions to the foregoing by setting up a hydrological model of the study area with a view to providing information on the sensitivity of the basin to climate change. With a model of the basin, projections of the future impacts of climate change will help to provide an understanding of the direction of change in rainfall and other hydrological parameters. Also, the study will provide quantitative information on the future impacts of climate change on water balance, runoff rates and volumes in the basin for better water resources planning and management, especially in agriculture. It is hoped that the success of the present study will inspire other researchers to apply hydrological models in other sub-catchment of the NRB in Nigeria. The study will help environmental managers and policy makers, especially water resources planners and managers, with the necessary information required for appropriate early warning systems against extreme events such as flood and drought, including adaptation and mitigation measures.

1.3 Research Objectives

The main objective of the study is to model the impacts of climate change on hydrology and water resources within the Nigerian catchment of the NRB, while the specific objectives are to:

(1) examine the trends of precipitation and temperature under the recent climate change in the NSB;
(2) assess the occurrences of droughts due to climate change impacts on water resources in the NSB;
(3) assess through modelling the impacts of climate change on the hydrology of the NSB; and
(4) evaluate the projected impacts of climate change on water resources in the NSB.

1.4 Scope and Limitations of the Study

The focus of this study is on the analysis of long term hydro-climatic data to assess the impacts of climate change on hydrology and water resources in the NSB, a sub-catchment of the Niger River Basin. It is also within the scope of the study to set up a hydrological model of the basin, calibrate and validate it with the aim of using the model to project into the future, the likely impacts of climate change on hydrology and water resources in the basin. For this purpose, the study will rely on secondary data of climate, discharge/streamflow, slope, soil and land use which are sourced from various data archiving agencies. In addition, projections of climate change are based on the output of general circulation models (GCMs) for both the mid and late 21st century. Thus, the results of the study are subject to the various limitations induced by the uncertainty in the GCMs and the errors in the data. The results of the study are also limited to the period of time covered by the data used.

1.5 Thesis Outline

Chapter one focuses on the general introduction to the work, gives the statement of the problem, the objectives of the study and the thesis outline. Chapter two centres on literature review which discusses the earth climate system, climate change, the Representative Concentration Pathway (RCP) and climate models. It also contains methods of downscaling, hydrological models, previous studies in the NRB, a brief discussion of the Soil and Water Assessment Tool (SWAT) model and the summary of all literature reviewed. Chapter three discusses the location of the study area, its topography, climate and hydrology. It further describes the data used, some of the statistical tools employed, the droughts indices used, the theoretical concepts of the hydrological model, SWAT and the general modelling procedure. Chapter four comprises of the results obtained and their discussions. Chapter five contains the conclusions drawn from the entire work, the major research findings and the recommendations for further studies. At the end, a short bio data of the candidate and a list of publications from the study are presented.

REFERENCES

Abaje, I.B., Ati, O.F. and Iguisi, E.O. (2010). An Analysis of Rainfall Trends in Kafanchan, Kaduna State, Nigeria. *Research Journal of Environmental and Earth Sciences* 2(2): 89-96.

Abbaspour, K.C. (2015). SWAT-CUP 2012: SWAT calibration and uncertainty programs- A user manual. Eawag Swiss Federal Institute of Aquatic Science and Technology, Switzerland.

Abbaspour, K.C., Rouholahnejad, E., Vaghefi, S., Srinivasan, R., Yang, H. and Kløve, B. (2015). A continental-scale hydrology and water quality model for Europe: Calibration and uncertainty of a high-resolution large-scale SWAT model. *Journal of Hydrology* 524: 733-752.

Abbaspour, K.C., Yang, J., Maximov, I., Siber, R., Bogner, K., Mieleitner, J., Zobrist, J. and Srinivasan, R. (2007). Modelling hydrology and water quality in the pre-alpine/alpine Thur watershed using SWAT. *Journal of hydrology* 333(2): 413-430.

Abiodun, B.J., Lawal, K.A., Salami, A.T. and Abatan, A.A. (2013). Potential influences of global warming on future climate and extreme events in Nigeria. *Regional Environmental Change* 13:477–491.

Abiola, S.F., Mohd-Mokhtar, R., Ismail, W. and Mohamad, N. (2013). Categorical statistical approach to satellite retrieved rainfall data analysis in Nigeria. *Scientific Research and Essays* 8(43): 2123-2137.

Abrate, T., Hubert, P. and Sighomnou, D. (2010). A Study on the hydrological series of the Niger River at Koulikoro, Niamey and Lokoja stations. In International Workshop on Advances in Statistical Hydrology. Taormina, Italy (pp. 1-10).

Abrate, T., Hubert, P. and Sighomnou, D. (2013). A study on hydrological series of the Niger River. *Hydrological Sciences Journal* 58(2): 271-279.

Adefolalu, D.O. (2007). Climate change and economic sustainability in Nigeria. In: Paper presented at the International Conference on Climate Change and Economic Sustainability held at Nnamdi Azikiwe University, Enugu, Nigeria, 12–14 June, 2007.

Aich, V., Koné, B., Hattermann, F.F. and Paton, E.N. (2016). Time Series Analysis of Floods Across the Niger River Basin. *Water* 8(165): 1-19.

Aich, V., Liersch S., Vetter, T., Huang, S., Tecklenburg, J., Hoffmann, P., Koch, H., Fournet, S., Krysanova, V., Müller, E.N. and Hattermann, F.F. (2014). Comparing impacts of climate change on streamflow in four large African river basins. *Hydrological Earth System Sciences* 18(4): 1305–1321.

Akinsanola, A.A. and Ogunjobi, K.O. (2014). Analysis of Rainfall and Temperature Variability over Nigeria. *Global Journal of Human-Social Science (B) Geography, Geo-Sciences, Environmental Disaster Management* 14(3): 1-18.

Allen, R.G., Pereira, L.S., Raes, D. and Smith, M. (1998). Crop evapotranspiration-Guidelines for computing crop water requirements- FAO Irrigation and drainage paper 56. FAO, Rome, 300(9), D05109.

Andersen, I. and Golitzen, K.G. (2005). The Niger river basin: A vision for sustainable management. World Bank Publications.

Angel, D.P., Attoh, S., Kromm, D., Dehart, J., Slocum, R. and White, S. (1998). The drivers of greenhouse gas emissions: what do we learn from local case studies? *Local Environment* 3(3): 263-277.

Angelina, A., Gado Djibo, A., Seidou, O., Seidou Sanda, I and Sittichok, K. (2015). Changes to flow regime on the Niger River at Koulikoro under a changing climate. *Hydrological Sciences Journal* 60(10): 1709-1723.

Anghileri, D., Pianosi, F. and Soncini-Sessa, R. (2015). Trend detection in seasonal data: from hydrology to water resources. *Journal of Hydrology* 511: 171–179.

Arnold, J.G. and Allen, P.M. (1996). Estimating hydrologic budgets for three Illinois watersheds. *Journal of hydrology* 176(1-4): 57-77.

Arnold, J.G. and Foher, N. (2005). SWAT 2000: current capabilities and research opportunities in applied watershed modelling. *Hydrological Processes* 19(3): 563–572.

Arnold, J.G., Engel, B.A. and Srinivasan, R. (1993). A continuous time, grid cell watershed model. *Application of advanced information technologies for management of natural resources*, 17-19.

Arnold, J.G., Kiniry, J.R., Srinivasan, R., Williams, J.R., Haney, E.B. and Neitsch, S.L. (2011). Soil and Water Assessment Tool input/output file documentation: Version 2009. Texas Water Resources Institute Technical Report, 365.

Arnold, J.G., Srinivasan, R., Muttiah, R.S. and Williams, J.R. (1998). Large area hydrologic modeling and assessment, Part I: Model development. *Journal of American Water Resources Association* 34: 73–89.

Awotwi, A., Kumi, M., Jansson P.E., Yeboah, F. and Nti, I.K. (2015). Predicting Hydrological Response to Climate Change in the White Volta Catchment, West Africa. *Journal of Earth System and Climatic Change* 6(1): 1-7.

Babatolu, J.S. and Akinnubi, R.T. (2014). Influence of climate change in Niger River Basin development authority area on Niger Runoff, Nigeria. *Journal of Earth Science & Climatic Change* 5(9): 1-8.

Bani-Domi, M. (2005). Trend Analysis of Temperatures and Precipitation in Jordan. Dept. of Geography Yarmouk University, Irbid–Jordan.

Bates, B., Kundzewicz, Z.W., Wu, S. and Palutikof, J. (2008). Climate change and water: Technical paper vi. Intergovernmental Panel on Climate Change (IPCC).

Beekman, H.E. (2006). Facing the facts: Assessing the vulnerability of Africa's water resources to environmental change (Vol. 2). UNEP/Earthprint.

Bekele, H.M. (2009). Evaluation of Climate Change Impact on Upper Blue Nile Basin Reservoirs (Case Study on Gilgel Abay Reservoir, Ethiopia). Unpublished MSc Thesis, School of Post Graduate Studies, Arba Minch University, Ethiopia.

Berg, A., de Noblet-Ducoudré, N., Sultan, B., Lengaigne, M. and Guimberteau, M. (2013). Projections of climate change impacts on potential C4 crop productivity over tropical regions. *Agricultural and Forest Meteorology* 170: 89-102.

Bergström, S. and Singh, V.P. (1995). The HBV model. *Computer Models of Watershed Hydrology*, 443-476.

Beven, K.J. (2011). Rainfall-runoff modelling: the primer. John Wiley & Sons, UK.

Blanco G., Gerlagh, R., Suh, S., Barrett, J., de Coninck, H.C., Diaz Morejon, C.F., Mathur, R., Nakicenovic, N., Ofosu Ahenkora, A., Pan, J., Pathak, H., Rice, J., Richels, R., Smith, S.J., Stern, D.I., Toth, F.L. and Zhou, P. (2014). Drivers, Trends and Mitigation. In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Bouraoui, F., Grizzetti, B., Granlund, K., Rekolainen, S. and Bidoglio, G. (2004). Impact of climate change on the water cycle and nutrient losses in a Finnish catchment. *Climatic Change* 66(1): 109-126.

Boyer, C., Chaumont, D., Chartier, I. and Roy, A.G. (2010). Impact of climate change on the hydrology of St. Lawrence tributaries. *Journal of Hydrology* 384: 65-83.

Brown, C., Greene, A., Block, P. and Giannini, A. (2008). Review of downscaling methodologies for Africa climate applications. International Research Institute for Climate and Society Columbia University, 15 April 2008 IRI Technical Report 08-05: IRI Downscaling Report

Brunetti, M., Maugeri, M., Monti, F. and Nanni, T. (2006). Temperature and precipitation variability in Italy in the last two centuries from homogenised instrumental time series. *International Journal of Climatology* 26: 345–381.

Busuioc, A., Giorgi, F., Bi, X. and Ionita, M. (2006). Comparison of regional climate model and statistical downscaling simulations of different winter precipitation change scenarios over Romania. *Theoretical and Applied Climatology* 86(1): 101-123.

Callaway, J.M. (2004). Adaptation benefits and costs: how important are they in the global policy picture and how can we estimate them? *Global Environmental Change* 14: 273–284.

Carson, R.T. (2010). The environmental Kuznets curve: seeking empirical regularity and theoretical structure. *Review of Environmental Economics and Policy* 4(1): 3-23.

Chaplot, V. (2007). Water and soil resources response to rising levels of atmospheric CO_2 concentration and to changes in precipitation and air temperature. *Journal of Hydrology* 337(1-2): 159-171.

Chen, G.S., Notaro, M., Liu, Z. and Liu, Y. (2012). Simulated local and remote biophysical effects of afforestation over the southeast United States in boreal summer. *Journal of Climate* 25(13): 4511-4522.

Cherie N.Z. (2013). Downscaling and Modeling the Effects of Climate Change on Hydrology and Water Resources in the Upper Blue Nile River Basin, Ethiopia. Unpublished PhD Dissertation, Department of Civil Engineering, University of Kassel, Germany.

Chien, H., Yeh, P.J.F. and Knouft, J.H. (2013). Modeling the potential impacts of climate change on streamflow in agricultural watersheds of the Midwestern United States. *Journal of Hydrology* 491: 73-88.

Chow, V.T., Maidment, D.R. and Mays, L.W. (1988). Applied Hydrology. MCGraw-Hill, USA.

Christensen, J.H., Hewitson, B., Busuioc, A., Chen, A., Gao, X., Held, R., ... & Magaña Rueda, V. (2007). Regional climate projections. Climate Change, 2007: The Physical Science Basis. Contribution of Working group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, University Press, Cambridge, Chapter 11, 847-940.

Clifton, C., Evans, R., Hayes, S., Hirji, R., Puz, G. and Pizarro, C. (2010). Water and climate change: impacts on groundwater resources and adaptation options. *Water Working Notes* 1: 1-76.

Conway, D. and Mahé, G. (2009). River flow modelling in two large river basins with non-stationary behaviour: the Paraná and the Niger. *Hydrological Processes* 23(22): 3186-3192.

Conway, D., Persechino, A., Ardoin-Bardin, S., Hamandawana, H., Dieulin, C. and Mahé, G. (2009). Rainfall and water resources variability in sub-Saharan Africa during the twentieth century. *Journal of Hydrometeorology* 10: 41–59.

Cook, K.H. and Vizy, E.K. (2006). Coupled model simulations of the West African monsoon system: Twentieth-and twenty-first-century simulations. *Journal of climate* 19(15): 3681-3703.

Dai, A. (2011). Drought under global warming: a review. Wiley Interdisciplinary Reviews: *Climate Change* 2(1): 45-65.

Daron, J.D. (2014). Regional Climate Messages: West Africa. Scientific report from the CARIAA adaptation at scale in Semi-Arid Regions (ASSAR) Project. scholar.google.com/scholar?q=%E2%80%9CRegional+Climate+Messages%3A+West+Africa%E2%80%9D&btnG=&hl=en&as_sdt=0%2C5

Devi, G.K., Ganasri, B.P. and Dwarakish, G.S. (2015). A Review on Hydrological Models. *Aquatic Procedia* 4: 1001-1007.

Dezetter, A., Girard, S., Paturel, J.E., Mahé, G., Ardoin-Bardin, S. and Servat, E. (2008). Simulation of runoff in West Africa: Is there a single data-model combination that produces the best simulation results?. *Journal of Hydrology* 354(1): 203-212.

Di Luzio, M., Srinivasan, R. and Arnold, J.G. (2002). Integration of Watershed Tools and the SWAT Model into BASINS. *Journal of American Water Resources Association* 38(4): 1127-1141.

Dinpashoh, Y., Jhajharia, D., Fakheri-Fard, A., Singh, V.P. and Kahya, E. (2011). Trends in reference crop evapotranspiration over Iran. *Journal of Hydrology* 399(3): 422-433.

Du, B., Ji, X., Harmel, R.D. and Hauck, L.M. (2009). Evaluation of a Watershed Model for Estimating Daily Flow Using Limited Flow Measurements. *Journal of The American Water Resources Association* 45(2): 475-484.

Dubus, I.G. and Brown, C.D. (2002). Sensitivity and first-step uncertainty analyses for the preferential flow model MACRO. *Journal of Environmental Quality* 31(1): 227–240.

Eckhardt, K. and Ulbrich, U. (2003). Potential impacts of climate change on groundwater recharge and streamflow in a central European low mountain range. *Journal of Hydrology* 284(1-4): 244-252.

Edwards, D.C. and McKee, T.B. (1997). Characteristics of 20th century drought in the United States at multiple time scales. Climatology Report 97-2, Department of Atmospheric Science, Colorado State University, Fort Collins, Colorado.

FAO (1995). Digital soil map of the world and derived soil properties (CDROM) Food and Agriculture Organization of the United Nations (FAO) Rome, Italy.

FAO (1997). Irrigation potential in Africa: A basin approach J. Plummer (Ed.) FAO Land and Water Bulletin 4.

FAO (2013). Towards more resilient societies. The High-level meeting on National Drought Policy, 11-15 March, 2013, Geneva, Switzerland.

Faramarzi, M., Abbaspour, K.C., Schulin, R. and Yang, H. (2009). Modelling blue and green water resources availability in Iran. *Hydrological Processes* 23(3): 486-209.

Faramarzi, M., Abbaspour, K.C., Vaghefi, S.A., Farzaneh, M.R., Zehnder, A.J.B., Srinivasan, R. and Yang, H. (2013). Modeling impacts of climate change on freshwater availability in Africa. *Journal of Hydrology* 480: 85–101.

Federal Ministry of Environment, Nigeria (2003). Nigeria's First National Communication under the United Nations Framework Convention on Climate Change. Abuja, Nigeria.

Ficklin, D.L., Luo, Y., Luedeling, E. and Zhang, M. (2009). Climate change sensitivity assessment of a highly agricultural watershed using SWAT. *Journal of Hydrology* 374: 16-29.

Fowler, H.J., Blenkinsop, S. and Tebaldi, C. (2007). Review Linking climate change modeling to impacts studies: Recent advances in downscaling techniques for hydrological modeling. *International Journal of Climatology* 27: 1547-1578.

Fu, G.B., Charles, S.P., Yu, J.J. and Liu, C.M. (2009). Decadal climatic variability, trends and future scenarios for the North China Plain. *Journal of Climate* 22: 2111–2123.

Fukunaga, D.C., Cecílio, R.A., Zanetti, S.S., Oliveira, L.T. and Caiado, M.A.C. (2015). Application of the SWAT hydrologic model to a tropical watershed at Brazil. *Catena* 125: 206-213.

Gachon, P. and Dibike, Y. (2007). Temperature change signals in northern Canada: convergence of statistical downscaling results using two driving GCMs. *International Journal of Climatology* 27(12): 1623-1641.

Gassman, P.W., Reyes, M., Green, C.H. and Arnold, J.G. (2007). The Soil and Water Assessment Tool: Historical development, applications, and future directins. *Transaction of American Society of Agricultural and Biological Engineers* 50(4): 1211-1250.

Gbobaniyi, E., Sarr, A., Sylla, M. B., Diallo, I., Lennard, C., Dosio, A., ... and Nikulin, G. (2014). Climatology, annual cycle and interannual variability of precipitation and temperature in CORDEX simulations over West Africa. *International Journal of Climatology* 34(7): 2241-2257.

Geist, H.J. and Lambin, E.F. (2002). Proximate Causes and Underlying Driving Forces of Tropical Deforestation Tropical forests are disappearing as the result of many pressures, both local and regional, acting in various combinations in different geographical locations. *BioScience* 52(2): 143-150.

Ghile, Y.B., Taner, M.Ü., Brown, C., Grijsen, J.G. and Talbi, A. (2014). Bottom-up climate risk assessment of infrastructure investment in the Niger River Basin. *Climatic Change* 122: 97–110.

Gocic, M. and Trajkovic, S. (2013a). Analysis of precipitation and drought data in Serbia over the period 1980–2010. *Journal of Hydrology* 494: 32–42.

Gocic, M. and Trajkovic, S. (2013b). Analysis of changes in meteorological variables using Mann-Kendall and Sen's slope estimator statistical tests in Serbia. *Global and Planetary Change* 100: 172-182.

Goosse, H., Barriat, P.Y., Lefebvre, W., Loutre, M.F. and Zunz, V. (2008). Introduction to Climate Dynamics and Climate Modelling. Université catholique de Louvain.

Gosain, A.K, Shrestha, A.B, Rao, S. (2010). Modelling climate change impact on the hydrology of the Eastern Himalayas; Climate change impact and vulnerability in the Eastern Himalayas – Technical report 4. Kathmandu: ICIMOD.

Gosain, A.K., Rao, S. and Basuray, D. (2006). Climate change impact assessment on hydrology of Indian river basins. *Current Science* 90(3): 346-353.

Grijsen, J.G., Brown, C., Tarhule, A., Ghile, Y.B., Taner, Ü., Talbi-Jordan, A., Doffou, H.N., Guero, A.D., Dessouassi, A.Y., Kone, S. and Coulibaly, B. (2013). Climate Risk Assessment for Water Resources Development in the Niger River Basin Part I: Context and Climate Projections.

Gupta, H.V., Sorooshian, S. and Yapo, P.O. (1999). Status of automatic calibration for hydrologic models: Comparison with multilevel expert calibration. *Journal of Hydrologic Engineering* 4(2): 135-143.

Hamed, K.H. (2008). Trend detection in hydrologic data: the Mann–Kendall trend test under the scaling hypothesis. *Journal of Hydrology* 349: 350–363.

Hamlet, A.L. and Lettenmaier, D. (1999). Effect of climate change on hydrology and water resources in the Columbia River basin. *Journal of the American Water Resources Association* 35(6): 1597-1623.

Hannaford, H. (2015). Climate-driven changes in UK river flows: A review of the evidence. *Progress in Physical Geography* 39(1): 29–48.

Hargreaves, G.L., Hargreaves, G.H. and Riley, J.P. (1985). Agricultural benefits for Senegal River Basin. *Journal of Irrigation and Drainage Engineering* 111(2): 113-124.

Hayes, M.J., Svoboda, M.D., Wall, N. and Widhalm, M. (2011). The Lincoln declaration on drought indices: universal meteorological drought index recommended. *Bulletin of American Meteorological Society* 92(4): 485–488.

Haylock, M.R., Cawley, G.C., Harpham, C., Wilby, R.L. and Goodess, C.M. (2006). Downscaling heavy precipitation over the UK: a comparison of dynamical and statistical methods and their future scenarios. *International Journal of Climatology* 26: 1397–1415.

Hernandez, E.A. and Uddameri, V. (2014). Standardized precipitation evaporation index (SPEI)-based drought assessment in semi-arid south Texas. *Environmental Earth Sciences* 71(6): 2491-2501.

Hertwich, E.G. and Peters, G.P. (2009). Carbon footprint of nations: A global, trade-linked analysis. *Environmental Science and Technology* 43(16): 6414-6420.

Hess, T.M., Stephens, W. and Maryah, U.M. (1995). Rainfall trends in the North East Arid Zone of Nigeria. *Agriculture and Forest Meteorology* 74: 87–97.

Hirsch, R.M., Slack, J.R. and Smith, R.A. (1982). Techniques of trend analysis for monthly water quality data. *Water Resources Research* 18(1): 107–121.

Hoerling, M., Kumar, A., Dole, R., Nielsen-Gammon, J.W., Eischeid, J., Perlwitz, J., Quan, X-W., Zhang, T., Pegion, P. and Chen, M. (2013). Anatomy of an extreme event. *Journal of Climate* 26(9): 2811–32.

Hulme, M., Doherty, R., Ngara, T., New, M. and Lister, D. (2001). African climate change: 1900-2100. *Climate Research* 17(2): 145-168.

Huntington, T.G. (2006). Evidence for intensification of the global water cycle: review and synthesis. *Journal of Hydrology* 319(1): 83-95.

Ingol Blanco, E.M. (2011). Modeling climate change impacts on hydrology and water resources: Case study Rio Conchos basin. PhD Dissertation Faculty of Graduate School, University of Texas at Austin, USA.

IPCC (2001). Climate Change 2001: The Scientific Basis, Technical Summary of the Working Group I Report (Houghton, J.T., Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, K. Maskell, and C.A. Johnson (eds.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC (2007). Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, Geneva, Switzerland, 104 pp.

IPCC (2013). Summary for Policymakers. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC (2014). Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Geneva, Switzerland, 151 pp.

ISRIC (2003). Soil and Terrain database for Southern Africa (1:2 million scale). In: FAO Land and Water Digital Media Series25. ISRC and FAO, Rome, Available at http://www.isric.org/data/soil-and-terrain-database-southern-africa-ver-10-sotersafFowler

Jain, S.K. and Kumar, V. (2012). Trend analysis of rainfall and temperature data for India. *Current Science* 102(1): 37-49.

Jakob, M., Marschinski, R. and Hübler, M. (2013). Between a rock and a hard place: a trade-theory analysis of leakage under production-and consumption-based policies. *Environmental and Resource Economics* 56(1): 47-72.

Jarvis, A., Reuter, H.I., Nelson, A. and Guevara E. (2006). Hole-filled seamless SRTM data V3, International Centre for Tropical Agriculture (CIAT), available from http://srtm.csi.cgiar.org.

Jayakrishnan, R., Srinivasan, R., Santhi, C. and Arnold, J.G. (2005). Advances in the application of the SWAT model for water resources management. *Hydrological Processes* 19: 749-762.

Jha, M., Pan, Z., Takle, E.S. and Gu, R. (2004). Impacts of climate change on streamflow in the Upper Mississippi River Basin: A regional climate model perspective. *Journal of Geophysical Research: Atmospheres* 109(D9).

Jhajharia, D., Dinpashoh, Y., Kahya, E., Singh, V.P. and Fakheri-Fard, A. (2012). Trends in reference evapotranspiration in the humid region of northeast India. *Hydrological Processes* 26(3): 421-435.

Joyce, B., Vicuña, S., Dale, L., Dracup, J., Hanemann, M., Purkey, D. and Yates, D. (2006). Climate change impacts on water for agriculture in California: A case study in the Sacramento Valley. Document de travail, California Climate Change Center, white Paper.

Jung, G. and Kunstmann, H. (2007). High-resolution regional climate modeling for the Volta region of West Africa. *Journal of Geophysical Research: Atmospheres* 112(D23).

Kahya, E. and Kalayci, S. (2004). Trend analysis of streamflow in Turkey. *Journal of Hydrology* 289: 128–144.

Kang, B. and Ramírez, J.A. (2007). Response of streamflow to weather variability under climate change in the Colorado Rockies. *Journal of Hydrologic Engineering* 12(1): 63-72.

Karavitis, C.A., Alexandris, S., Tsesmelis, D.E. and Athanasopoulos, G. (2011). Application of the Standardized Precipitation Index (SPI) in Greece. *Water* 3: 787-805.

Karpouzos, D.K., Kavalieratou, S. and Babajimopoulos, C. (2010). Trend analysis of precipitation data in Pieria Region (Greece). *European Water* 30: 31-40.

Kasei, R.A. (2009). Modelling impacts of climate change on water resources in the Volta Basin, West Africa. Unpublished PhD Thesis, University of Bonn, Germany.

Kendall, M.G. (1975). Rank Correlation Methods. Charles Griffin, London.

Kiehl, J.T. and Trenberth, K.E. (1997). Earth's annual global mean energy budget. *Bulletin of the American Meteorological Society* 78(2): 197-208.

Kiely, G. (1999). Climate change in Ireland from precipitation and streamflow observations. *Advances in water resources* 23(2): 141-151.

Kim, J., Waliser, D.E., Mattmann, C.A., Goodale, C.E., Hart, A.F., Zimdars, P.A., ... and Jack, C. (2014). Evaluation of the CORDEX-Africa multi-RCM hindcast: systematic model errors. *Climate Dynamics* 42(5-6): 1189-1202.

Koch, M. (2008). Challenges for future sustainable water resources management in the face of climate change, The 1st NPRU Academic Conference, Nakhon Pathom University, Thailand.

Kothawale, D.R., Revadekar, J.V. and Kumar, R.K. (2010). Recent trends in pre-monsoon daily temperature extremes over India. *Journal of Earth System Science* 119: 51–65.

Kumar, V., Jain, S.K. and Singh, Y. (2010). Analysis of long-term rainfall trends in India. *Hydrological Sciences Journal* 55(4): 484-496.

Kundzewicz, Z. and Robson, A. (2004). Change detection in hydrological records – a review of the methodology. *Hydrological Sciences Journal* 49: 7–19.

L'Hóte, Y., Mahe, G., Some, B. and Triboulet, J.P. (2002). Analysis of a Sahelian annual rainfall index from 1896 to 2000; the drought continues. *Hydrological Sciences Journal* 48(3): 489–496.

Le Barbe, L. and Lebel. T. (1997). Rainfall Climatology of the HAPEX-Sahel Region during the Years 1950–1990. *Journal of Hydrology* 188(1): 43–73.

Legesse, D., Vallet-Coulomb, C. and Gasse, F. (2003). Hydrological response of a catchment to climate and land use changes in Tropical Africa: case study South Central Ethiopia. *Journal of Hydrology* 275: 67-85.

Lelis, T.A., Calijuri, M.L., Santiago, A.D.F., Lima, D.C.D. and Rocha, E.D.O. (2012). Sensitivity analysis and calibration of SWAT model applied to a watershead in southeastern Brazil. *Revista Brasileira de Ciência do Solo* 36(2): 623-634.

Li, K.Y., Coe, M.T., Ramankutty, N. and De Jong, R. (2007). Modeling the hydrological impact of land-use change in West Africa. *Journal of Hydrology* 337(3): 258-268.

Liang, L., Li, L. and Liu, Q. (2011). Precipitation variability in Northeast China from 1961 to 2008. *Journal of Hydrology* 404(1): 67-76.

Liang, X., Lettenmaier, D.P., Wood, E.F. and Burges, S.J. (1994). A simple hydrologically based model of land surface water and energy fluxes for general circulation models. *Journal of Geophysical Research: Atmospheres* 99(D7): 14415-14428.

Lienou, G. (2013). Integrated future needs and climate change on the River Niger water availability. *Journal of Water Resource and Protection* 5(9): 887-893.

Lim, H.J., Yoo, S.H. and Kwak, S.J. (2009). Industrial CO_2 emissions from energy use in Korea: a structural decomposition analysis. *Energy Policy* 37(2): 686-698.

Liu, J., Song, M., Horton, R.M. and Hu, Y. (2013). Reducing spread in climate model projections of a September ice-free Arctic. *Proceedings of the National Academy of Sciences* 110(31): 12571-12576.

Liu, Z., Notaro, M., Kutzbach, J. and Liu, N. (2006). Assessing global vegetation climate feedbacks from observations. *Journal of Climate* 19(5): 787-814.

Lloyd-Hughes, B. and Saunders, M.A. (2002). A drought climatology for Europe. *International Journal of Climatology* 22(13): 1571-1592.

Longobardi, A. and Villani, P. (2010). Trend analysis of annual and seasonal rainfall time series in the Mediterranean area. *International Journal of Climatology* 30(10): 1538–1546.

Lorenzo-Lacruz, J., Vicente-Serrano, S.M., López-Moreno, J.I., Beguería, S., García-Ruiz, J.M. and Cuadrat, J.M. (2010). The impact of droughts and water management on various hydrological systems in the headwaters of the Tagus River (central Spain). *Journal of Hydrology* 386: 13–26.

Loukas, A. and Quick, M.C. (1996). Effect of climate change on hydrologic regime of two climatically different watersheds. *Journal of Hydrologic Engineering* 1(2): 77-87.

Ma, X., Lu, X.X., van Noordwijk, M., Li, J.T. and Xu, J.C. (2014). Attribution of climate change, vegetation restoration, and engineering measures to the reduction of suspended sediment in the Kejie catchment, southwest China. *Hydrology and Earth System Sciences* 18(5): 1979-1994.

Ma, X., Xu, J., Luo, Y., Prasad Aggarwal, S. and Li, J. (2009). Response of hydrological processes to land-cover and climate changes in Kejie watershed, south-west China. *Hydrological Processes* 23(8): 1179-1191.

Mahé, G. and Paturel, J.E. (2009). 1896–2006 Sahelian annual rainfall variability and runoff increase of Sahelian Rivers. *Comptes Rendus Geoscience* 341(7): 538-546.

Mahe, G., Lienou, G., Descroix, L., Bamba, F., Paturel, J. E., Laraque, A., Meddi, M., Habaieb, H., Adeaga, O., Dieulin, C., Chahnez Kotti, F. and Khomasi, K. (2013). The rivers of Africa: witness of climate change and human impact on the environment. *Hydrological Processes* 27(15): 2105-2114.

Mahoo, H.F., Young, M.D.B. and Mzirai, O.B. (1999). Rainfall Variability and its Implications for the Transferability of Experimental Results in the Semi-Arid areas of Tanzania. *Tanzania Journal of Agricultural Sciences* 2(2): 127–140.

Malla, S. (2009). CO_2 emissions from electricity generation in seven Asia-Pacific and North American countries: A decomposition analysis. *Energy Policy* 37(1): 1-9.

Mango, L.M., Melesse, A.M., McClain, M.E., Gann, D. and Setegn, S.G. (2011). Land use and climate change impacts on the hydrology of the upper Mara River Basin, Kenya: results of a modeling study to support better resource management. *Hydrology and Earth System Sciences* 15(7): 2245-2258.

Mann, H.B. (1945). Nonparametric tests against trend. *Econometrica* 13: 245–259.

Masih, I., Maskey, S., Mussá, F.E.F. and Trambauer, P. (2014). A review of droughts on the African continent: a geospatial and long-term perspective. *Hydrology and Earth System Sciences* 18(9): 3635-3649.

McCabe Jr, G.J. and Hay, L.E. (1995). Hydrological effects of hypothetical climate change in the East River basin, Colorado, USA. *Hydrological Sciences Journal* 40(3): 303-318.

McKee, T.B., Doesken, N.J. and Kleist, J. (1993). The relationship of drought frequency and duration to time scale. In: Proceedings of the Eighth Conference on Applied Climatology, Anaheim, California, 17–22 January 1993. Boston, *American Meteorological Society*, 179–184.

Meigh, J.R., McKenzie, A.A. and Sene, K.J. (1999). A grid-based approach to water scarcity estimates for eastern and southern Africa. *Water Resources Management* 13: 85–115.

Memarian, H., Balasundram, S.K., Abbaspour, K.C., Talib, J.B., Boon Sung, C.T. and Sood, A.M. (2014). SWAT-based hydrological modelling of tropical land-use scenarios. *Hydrological Sciences Journal* 59(10): 1808-1829.

Mengistu, D.T. and Sorteberg, A. (2012). Sensitivity of SWAT simulated streamflow to climatic changes within the Eastern Nile River basin. *Hydrology and Earth System Sciences* 16(2): 391-407.

Meza, F.J. (2013). Recent trends and ENSO influence on droughts in Northern Chile: An application of the Standardized Precipitation Evapotranspiration Index. *Weather and Climate Extremes* 1: 51–58.

Miao, L.I, Jun, X. and Dejuan, M. (2012). Long-term Trend Analysis of Seasonal Precipitation for Beijing, China. *Journal of Resources and Ecology* 3(1): 064-072.

Middelkoop, H., Daamen, K., Gellens, D., Grabs, W., Kwadijk, J.C., Lang, H., ... and Wilke, K. (2001). Impact of climate change on hydrological regimes and water resources management in the Rhine basin. *Climatic change* 49(1-2): 105-128.

Mishra, A.K. and Desai, V.R. (2005). Spatial and temporal drought analysis in the Kansabati river basin, India. *International Journal of River Basin Management* 3(1): 31-41.

Mishra, A.K. and Singh, V.P. (2010). A review of drought concepts. *Journal of Hydrology* 391: 202–216.

Mishra, S.K. (2013). Modeling water quantity and quality in an agricultural watershed in the midwestern US using SWAT: assessing implications due to an expansion in 'biofuel' production and climate change. PhD Thesis, University of Iowa, USA.

Mitchell, T.D. and Jones, P.D. (2005). An improved method of constructing a database of monthly climate observations and associated high-resolution grids. *International Journal of Climatology* 25: 693–712.

Mitchell, T.D., Hulme, M. and New, M. (2002). Climate data for political areas. *Area* 34(1): 109-112.

Mohamed, A.B. (2011). Climate change risks in Sahelian Africa. Regional *Environmental Change* 11(1): 109-117.

Monteith, J.L. (1965). Evaporation and environment. *Symposia of the Society for Experimental Biology*, 19: 205-234.

Moriasi, D.N. and Starks, P.J., (2010). Effects of the resolution of soil dataset and precipitation dataset on SWAT2005 streamflow calibration parameters and simulation accuracy. *Journal of Soil and Water Conservation* 65(2): 163–178.

Moriasi, D.N., Arnold, J.G., Van Liew, M.W., Bingner, R.L., Harmel, R.D. and Veith, T.L. (2007). Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. *Transactions of The ASABE* 50(3): 885-900.

Musau, J., Sanga, J., Gathenyaa, J. and Luedelingb, E. (2015). Hydrological responses to climate change in Mt. Elgon watersheds. *Journal of Hydrology: Regional Studies* 3: 233–246.

Nalbantis, I. and Tsakiris, G. (2009). Assessment of hydrological drought revisited. *Water Resources Management* 23(5): 881–897.

Nansai, K., Kagawa, S., Suh, S., Fujii, M., Inaba, R. and Hashimoto, S. (2009). Material and energy dependence of services and its implications for climate change. *Environmental Science and Technology* 43(12): 4241-4246.

Nash, J.E. and Sutcliffe, J.V. (1970). River flow forecasting through conceptual models part I—A discussion of principles. *Journal of Hydrology* 10(3): 282-290.

National Bureau of Statistics (2006). The Nigeria Population Commission (NPC) Official Result for 2006 Population and Housing Census Figures, Bureau for National Statistics, Abuja. http://www.nigerianstat.gov.ng

Neelin, J.D. (2011). Climate Change and Climate Modeling. Cambridge University Press, Cambridge CB2 8RU, UK. Pp. 289.

Neitsch, S., Arnold, J., Kiniry, J., Williams, J.R. and King, K.W. (2011). SWAT2009 Theoretical Documentation. Texas Water Ressources Institute Technical Report, (406).

Neitsch, S.L, Arnold, J.G., Kiniry, J.R. and Williams, J.R. (2005). Soil and Water Assessment Tool Theoretical Documentation - Version 2005, Grassland, Soil & Water Research Laboratory, Agricultural Research Service, and Blackland Agricultural Research Station, Temple, Texas.

Neitsch, S.L., Arnold, J.G., Kiniry, J.R. and Srinivasan, R.W. (2002). Soil and Water Assessment Tool User's Manual –Version 2000. U.S. Department of Agriculture, Agricultural Research Service, Temple, TX.

New, M., Hulme, M. and Jones, P.D. (2000). Representing twentieth century space-time climate variability. Part II: Development of a 1961–90 Mean monthly terrestrial climatology. *Journal of Climate* 13: 2217–2238.

Nicholson, S.E. (2001). Climatic and environmental change in Africa during the last two centuries. *Climate Research* 17: 123-144.

Nicholson, S.E., Some, B. and Kone, B. (2000). An analysis of recent rainfall conditions in West Africa, including the rainy seasons of the 1997 El Nino and the 1998 La Nina years. *Journal of Climate* 13(14): 2628–2640.

O'Neill B.C., Dalton, M., Fuchs, R., Jiang, L., Pachauri, S. and Zigova, K. (2010). Global demographic trends and future carbon emissions. *Proceedings of the National Academy of Sciences of the United States of America* 107: 17521 – 17526. www.scopus. com/ inward / record.url?eid=2-s2.0

Ogilvie, A., Mahé, G., Ward, J., Serpantié, G., Lemoalle, J., Morand, P., ... and Kaczan, D. (2010). Water, agriculture and poverty in the Niger River basin. *Water International* 35(5): 594-622.

Oguntunde, P.G. and Abiodun, B.J. (2013). The impact of climate change on the Niger River Basin hydroclimatology, West Africa. *Climate Dynamics* 40(1-2): 81-94.

Oguntunde, P.G., Abiodun, B.J. and Lischeid, G. (2011). Rainfall trends in Nigeria, 1901–2000. *Journal of Hydrology* 411: 207–218.

Oguntunde, P.G., Abiodun, B.J. and Lischeid, G. (2012). Spatial and temporal temperature trends in Nigeria, 1901–2000. *Meteorology and Atmospheric Physics* 118(1-2): 95-105.

Oguntunde, P.G., Abiodun, B.J. and Lischeid, G. (2015). A numerical modelling study of the hydroclimatology of the Niger River Basin, West Africa. *Hydrological Sciences Journal* 61(1): 94-106.

Oguntunde, P.G., Friesen, J., van de Giesen, N. and Savenije, H.H. (2006). Hydroclimatology of the Volta River Basin in West Africa: trends and variability from 1901 to 2002. *Physics and Chemistry of the Earth, Parts A/B/C* 31(18): 1180-1188.

Okpara, J.N., Tarhule, A.A. and Perumal, M. (2013). Study of Climate Change in Niger River Basin, West Africa: Reality Not a Myth. Climate Change–Realities, Impacts over Ice-cap, Sea Level and Risks, 1, Pp36.

Olaniran, O.J. (2002). Rainfall Anomalies in Nigeria: The Contemporary Understanding. The 55th Inaugural Lecture. University of Ilorin, Nigeria, pp. 55.

Olomoda, I.A. (2012). Challenges of Continued River Niger Low Flow into Nigeria. *Hydrology for Disaster Management Special Publication of the Nigerian Association of Hydrological Sciences*, 145-155.

Olomoda, I.A. and Jaege, M. (2012). Impact of Climate Change on Transboundary Water Resources: the Case Study of the River Niger Basin. BALWOIS, 28th May -2nd June, Ohrid, Republic of Macedonia.

Oluleye, A. (2009). Change detection in rainfall anomalies across climatic zones in Nigeria. *Journal of Meteorology and Climate Science* 7: 6-10.

Oyama, M.D. and Nobre, C.A. (2004). Climatic consequences of a large-scale desertification in northeast Brazil: A GCM simulation study. *Journal of Climate* 17(16): 3203-3213.

Paeth, H., Fink, A. and Samimi, C. (2009). The 2007 flood in sub-Saharan Africa: spatio-temporal characteristics, potential causes, and future perspective. In 9th EMS Annual Meeting, 9th European Conference on Applications of Meteorology (ECAM) Abstracts, held Sept. 28-Oct. 2, 2009 in Toulouse, France. http://meetings. copernicus. org/ems2009/, id. EMS2009-103. (Vol. 1, p. 103).

Panagopoulos, Y., Gassman, P.W., Arritt, R.W., Herzmann, D.E., Campbell, T.D., Valcu, A., ... and Arnold, J.G. (2015). Impacts of climate change on hydrology, water quality and crop productivity in the Ohio-Tennessee River Basin. *International Journal of Agricultural and Biological Engineering* 8(3): 36-53.

Parry, M.L., Canziani, O.F., Palutikof, J.P., Van der Linden, P.J. and Hanson, C.E. (2007). Contribution of working group II to the fourth assessment report of the intergovernmental panel on climate change, 2007. Climate Change 2007: Working Group II: Impacts, Adaptation and Vulnerability.

Paulo, A.A. Rosal, R.D. and Pereira, L.S. (2012). Climate trends and behaviour of drought indices based on precipitation and evapotranspiration in Portugal. *Natural Hazards and Earth System Sciences* 12: 1481–1491.

Pervez, M.S. and Henebry, G.M. (2015). Assessing the impacts of climate and land use and land cover change on the freshwater availability in the Brahmaputra River basin. *Journal of Hydrology: Regional Studies* 3: 285-311.

Peters, G.P., Minx, J.C., Weber, C.L. and Edenhofer, O. (2011). Growth in emission transfers via international trade from 1990 to 2008. *Proceedings of the National Academy of Sciences* 108(21): 8903-8908.

Pinto, D.B.F., da Silva, A.M., Beskow, S., de Mello, C.R. and Coelho, G. (2013). Application of the Soil and Water Assessment Tool (SWAT) for sediment transport simulation at a headwater watershed in Minas Gerais State, Brazil. *Transactions of The ASABE* 56(2): 697-709.

Priestley, C.H.B. and Taylor, R.J. (1972). On the assessment of surface heat flux and evaporation using large-scale parameters. *Monthly Weather Review* 100: 81-92.

Randall, D.A., Wood, R.A., Bony, S., Colman, R., Fichefet, T., Fyfe, J., ... and Stouffer, R. J. (2007). Cilmate models and their evaluation. climate change 2007: The physical science basis. Contribution of working group I to the fourth assessment report of the Intergovernmental Panel on Climate Change. Solomon S, Qin D. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Refsgaard, J. and Storm, B. (1995). MIKE SHE. In: Singh (eds.), Computer models of watershed hydrology (pp. 809–846). Water Resources Publication CO., USA.

Riahi, K., Grübler, A. and Nakicenovic, N. (2007). Scenarios of long-term socio-economic and environmental development under climate stabilization. *Technological Forecasting and Social Change* 74(7): 887-935.

Rogelj, J., Meinshausen, M. and Knutti, R. (2012). Global warming under old and new scenarios using IPCC climate sensitivity range estimates. *Nature Climate Change* 2(4): 248-253.

Rosso, F.V., Boiask, N.T., Ferraz, S.E.T., Dewes, C.F. and Tatsch, J.D. (2015). Trends and Decadal Variability in Air Temperature over Southern Brazil. *American Journal of Environmental Engineering* 5(1A): 85-95.

Rouault, M. and Richard, Y. (2003). Intensity and spatial extension of drought in South Africa at different time scales. *Water SA*, 29(4), 489-500.

Rowell, D.P., Senior, C.A., Vellinga, M. and Graham, R.J. (2016). Can climate projection uncertainty be constrained over Africa using metrics of contemporary performance? *Climatic Change* 134(4): 621-633.

Salami, A.W., Mohammed, A.A., Abdulmalik, Z.A. and Olanlokun, O.K. (2014). Trend Analysis of Hydro-Meteorological Variables using The Mann-Kendall Trend Test: Application to The Niger River and The Benue Sub-Basins in Nigeria. *International Journal of Technology* 2: 100-110.

Salmi, T., Maatta, A., Anttila, P., Ruoho-Airola, T. and Amnell, T. (2002). Detecting Trends of Annual Values of Atmospheric Pollutants by the Mann-Kendall Test and Sen's Slope Estimates. Publications on Air Quality, No. 31. Helsinki, Finland.

Samuelsson, P., Jones, C.G., Willén, U., Ullerstig, A., Gollvik, S., Hansson, U.L.F., ... and Wyser, K. (2011). The Rossby Centre Regional Climate model RCA3: model description and performance. *Tellus* 63A(1): 4-23.

Sarr, B. (2012). Present and future climate change in the semi-arid region of West Africa: a crucial input for practical adaptation in agriculture. *Atmospheric Science Letters*, 1-5.

Schuol, J. and Abbaspour, K.C. (2006). Calibration and uncertainty issues of a hydrological model (SWAT) applied to West Africa. *Advances in Geosciences* 9: 137–143.

Schuol, J. and Abbaspour, K.C. (2007). Using monthly weather statistics to generate daily data in a SWAT model application to West Africa. *Journal of Ecological Modelling* 201(3-4): 301–311.

Schuol, J., Abbaspour, K.C., Yang, H., Srinivasan, R. and Zehnder, A.J. (2008). Modelling blue and green water availability in Africa. *Water Resources Research* 44(7).

Segele, Z.T., Leslie, L.M. and Lamb, P.J. (2009). Evaluation and adaptation of a regional climate model for the Horn of Africa: rainfall climatology and interannual variability. *International Journal of Climatology* 29(1): 47-65.

Seiler, R.A., Hayes, M. and Bressan, L. (2002). Using the standardized precipitation index for flood risk monitoring. *International Journal of Climatology* 22(11): 1365-1376.

Sellami, H., La Jeunesse, I., Benabdallah, S., Baghdadi, N. and Vanclooster, M. (2014). Uncertainty analysis in model parameters regionalization: a case study involving the SWAT model in Mediterranean catchments (Southern France). *Hydrology and Earth System Sciences* 18: 2393- 2413.

Sen, P.K. (1968). Estimates of the regression coefficient based on Kendall's tau. *Journal of American Statistical Association* 63: 1379–1389.

Setegn S.G., Srinivasan, R., Melesse, A.M. and Dargahi, B. (2009). SWAT model application and prediction uncertainty analysis in the Lake Tana Basin, Ethiopia. *Hydrological Processes* 23(26): 3738–3750.

Setegn, S.G., Srinivasan, R. and Dargahi, B. (2008). Hydrological Modelling in the Lake Tana Basin, Ethiopia Using SWAT Model. *The Open Hydrology Journal* 2: 49-62.

Sharma, K.D., Sorooshian, S. and Wheater, H. (2008). Hydrological Modelling in Arid and Semi-Arid Areas. Cambridge University Press, New York, 223Pp.

Sherbinin, M.E., Fischer, A., Levy, M., Schnarr, E., Simon, C., Sundareshwar, P.V. and Trzaska, S. (2013). Background Paper for the ARCC West Africa Regional Climate Change Vulnerability Assessment.

Shrestha, M.S., Artan, G.A., Bajracharya, S.R. and Sharma, R. (2008). Using satellite-based rainfall estimates for streamflow modeling: Bagmati Basin. *Journal of Flood Risk Management* 1: 89-99.

Shrestha, S., Shrestha, M. and Babel, M.S. (2016). Modelling the potential impacts of climate change on hydrology and water resources in the Indrawati River Basin, Nepal. *Environmental Earth Sciences* 75(4): 1-13.

Shukla, S. and Wood, A.W. (2008). Use of a standardized runoff index for characterizing hydrologic drought. *Geophysical Research Letters* 35(2).

SNAP (2011). Yukon Water Availability Analysis, Yukon, Canada. https://www.snap.uaf.edu/sites/default/files/yukon_pet_report.pdf

Solomon, S., Qin D., Manning M., Chen Z., Marquis, M., Averyt K.B., Tignor, M. and Miller H.L. (eds) (2007). Climate change 2007: the physical science basis, Contribution of working group I to the fourth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge and New York, NY.

Sonali, P. and Kumar, D.N. (2013). Review of trend detection methods and their application to detect temperature changes in India. *Journal of Hydrology* 476: 212–227.

Suh, S. (2006). Are Services Better for Climate Change? *Environmental Science & Technology*, 40(21): 6555–6560.

Sulis, M., Marrocu, M. and Paniconi, C. (2009). Conjunctive use of a hydrological model and a multicriteria decision support system for a case study on the Caia catchment, Portugal. *Journal of Hydrologic Engineering*, 14(2), 141-152.

Sultan, B., Roudier, P., Quirion, P., Alhassane, A., Muller, B., Dingkuhn, M., Ciais, P., Guimberteau, M., Traore, S. and Baron, C. (2013). Assessing climate change impacts on sorghum and millet yields in the Sudanian and Sahelian savannas of West Africa. *Environmental Research Letters* 8: 014040, doi:10.1088/1748-9326/8/1/014040.

Tabari, H. and Hosseinzadeh Talaee, P. (2011). Analysis of trends in temperature data in arid and semi-arid regions of Iran. *Global and Planetary Change* 79(1): 1-10.

Tabari, H., Nikbakht, J. and Hosseinzadeh Talaee, P. (2013). Hydrological Drought Assessment in Northwestern Iran Based on Streamflow Drought Index (SDI). *Water Resources Management* 27: 137–151.

Tabari, H., Somee, B.S. and Zadeh, M.R. (2011). Testing for long-term trends in climatic variables in Iran. *Atmospheric Research* 100(1): 132-140.

Tang, C., Crosby, B.T., Wheaton, J.M., and Piechota, T.C. (2012). Assessing streamflow sensitivity to temperature increases in the Salmon River Basin, Idaho. *Global and Planetary Change* 88: 32-44.

The Punch (2012). Kogi lost N40bn to floods. The Punch Newspaper, 28th September, 2012.

Thom, H.C.S. (1966). Some Methods of Climatological Analysis. WMO Technical Note Number 81. Secretariat of the World Meteorological Organization, Geneva, Switzerland.

Thornthwaite, C.W. (1948). An approach toward a rational classification of climate. *Geographical Review* 38(1): 55-94.

Torrence, C. and Compo, G.P. (1998). A practical guide to wavelet analysis. *Bulletin of the American Meteorological Society* 79(1): 61-78.

Trenberth, K.E., Dai, A., Van Der Schrier, G., Jones, P.D., Barichivich, J., Briffa, K.R. and Sheffield, J. (2014). Global warming and changes in drought. *Nature Climate Change* 4(1): 17-22.

Turkes, M. (1996). Spatial and temporal analysis of annual rainfall variations in Turkey. *International Journal of Climatology* 16(9): 1057-1076.

Türkes, M. and Sümer, U.M. (2004). Spatial and temporal patterns of trends and variability in diurnal temperature ranges of Turkey. *Theoretical and Applied Climatology* 77(3–4): 195–227.

Ujeneza, E.L. and Abiodun, B.J. (2015). Drought regimes in Southern Africa and how well GCMs simulate them. *Climate Dynamics* 44: 1595–1609.

UNDP (2013). Human Development Report 2013. The rise of the South: Human Progress in a Diverse World. UNDP-HDRO Human Development Reports.

UNFCC (2007). United Nations Climate Change Conference, Nusa Dua, Bali, Indonesia, 3rd- 5th December, 2007. http://unfccc.int/meetings/cop_13/items/4049.php.

Urama, K. C. and Ozor, N. (2010). Impacts of climate change on water resources in Africa: the role of adaptation. *African Technology Policy Studies Network* 29: 1-29.

Van de Giesen, N., Liebe, J. and Jung, G. (2010). Adapting to climate change in the Volta Basin, West Africa. *Current Science* 98(8): 1033-1037.

Van Griensven, A., Ndomba, P., Yalew, S. and Kilonzo, F. (2012). Critical review of SWAT applications in the upper Nile basin countries. *Hydrology and Earth System Sciences 16(9)*: 3371–3381.

Van Vliet, M.T.H., Franssen, W.H.P., Yearsley, J.R., Ludwig, F., Haddeland, I., Lettenmaier, D.P. and Kabat, P. (2013). Global river discharge and water temperature under climate change. *Global Environmental Change* 23: 450–464.

Varis, O., Kajander, T. and Lemmelä, R. (2004). Climate and water: from climate models to water resources management and vice versa. *Climatic Change* 66(3): 321-344.

Vasiliades, L., Loukas, A. and Liberis, N. (2010). A water balance derived drought index for Pinios River Basin, Greece. *Water Resources Management* 25(4): 1087–1101.

Vicente-Serrano, S.M., Beguería, S. and López-Moreno, J.I. (2010). A multiscalar drought index sensitive to global warming: the standardized precipitation evapotranspiration index. *Journal of Climate* 23(7): 1696-1718.

Vicente-Serrano, S.M., López-Moreno, J.I., Beguería, S. Lorenzo-Lacruz, J., Azorin-Molina, C. and Morán-Tejeda, E. (2012). Accurate Computation of a Streamflow Drought Index. *Journal of Hydrologic Engineering* 17: 318-332.

Vigaud, N., Roucou, P., Fontaine, B., Sijikumar, S. and Tyteca, S. (2011). WRF/ARPEGE-CLIMAT simulated climate trends over West Africa. *Climate Dynamics* 36(5-6): 925-944.

Viner, D. (2000). Modelling Climate Change, University of East Anglia, UK. www.cru.uea.ac.uk/modelling-climate-change.

Vose, R.S., Easterling, D.R. and Gleason, B. (2005). Maximum and minimum temperature trends for the globe: An update through 2004. *Geophysical Research Letters* 32: 1-5.

Wang, D., Hejazi,M., Cai, X. and Valocchi, A.J. (2011). Climate change impact on meteorological, agricultural, and hydrological drought in central Illinois. *Water Resources Research* 47: W09527, doi:10.1029/2010WR009845.

Whitehead, P.G., Wilby, R.L., Battarbee, R.W., Kernan, M. and Wade, A.J. (2009). A review of the potential impacts of climate change on surface water quality. *Hydrological Sciences Journal* 54(1): 101-123.

Wier, M., Lenzen, M., Munksgaard, J. and Smed, S. (2001). Effects of household consumption patterns on CO_2 requirements. *Economic Systems Research* 13(3): 259-274.

Wilby, R. L., Whitehead, P.G., Wade, A.J., Butterfield, D., Davis, R.J. and Watts, G. (2006). Integrated modelling of climate change impacts on water resources and quality in a lowland catchment: River Kennet, UK. *Journal of Hydrology* 330(1): 204-220.

Wilby, R.L. and Dawson, C.W. (2007). Using SDSM Version 4.1 SDSM 4.2. 2—a decision support tool for the assessment of regional climate change impacts. User Manual, Leicestershire, UK.

Wilby, R.L. and Harris, I. (2006). A framework for assessing uncertainties in climate change impacts: low flow scenarios for the River Thames, UK. *Water Resources Research*, 42(2).

Wilby, R.L., Dawson, C.W. and Barrow, E.M. (2002). SDSM—a decision support tool for the assessment of regional climate change impacts. *Environmental Modelling & Software*, 17(2): 145-157.

Wilby, R.L., Lauren E. Hay, William J. Gutowski Jr., Raymon W. Arrittt, Eugene S. Takle, Zaitao Pan, Georg H. Leavesley, Martyn P. Clark (2000). Hydrological responses to dynamically and statistically downscaled climate model output. *Geophysical Research Letters* 27 (8): 1199-1202.

Wilby, R.L., Troni, J., Biot, Y., Tedd, L., Hewitson, B.C. Smith, D.M. and Sutton, R.T. (2009). A review of climate risk information for adaptation and development planning. *International Journal of Climatology* 29(9): 1193-1215.

Wilhite, D.A. (2005). Drought and water crises: science, technology, and management issues, 86. CRC Press, USA.

WMO (1975). Drought and Agriculture. WMO/ TN 138, Geneva.

WMO (1988). Analyzing long time series of hydrological data with respect to climate variability. World Meteorological Organization (WMO): WCAP-3, WMO/TD-No: 224, Switzerland, pp. 1–12.

WMO (2012). Standard Precipitation Index User Guide. WMO-No.1090, http://www.wamis.org/agm/pubs/SPI/WMO_1090_EN.pdf, 24th March, 2015.

Wu, W., Lynch, A.H. and Rivers, A. (2005). Estimating the uncertainty in a regional climate model related to initial and lateral boundary conditions. *Journal of Climate* 18(7): 917-933.

Xu, C.-Y. (1999). From GCMs to river flow: a review of downscaling methods and hydrologic modelling approaches. *Progress in Physical Geography* 23(2): 229-249.

Xu, C.-Y. (2000). Modelling the Effects of Climate Change on Water Resources in Central Sweden. *Water Resources Management* 14: 177-189.

Xu, Z., Liu, Z., Fu, G. and Chen, Y. (2010). Trends of major hydroclimatic variables in the Tarim River basin during the past 50 years. *Journal of Arid Environment* 74: 256–267.

Yang, J., Reichert, P., Abbaspour, K.C., Xia, J. and Yang, H. (2008). Comparing uncertainty analysis techniques for a SWAT application to the Chaohe Basin in China. *Journal of Hydrology* 358(1): 1-23.

Yates, D.N. and Strzepek, K.M. (1998). Modeling the Nile Basin under climatic change. *Journal of Hydrologic Engineering* 3(2): 98-108.

Zhang, G.H., Nearing, M. and Liu, B.Y. (2005). Potential effects of climate change on rainfall erosivity in the Yellow River basin of China. *Transactions of The ASA*E 48(2): 511-517.

Zhao, L., Lyu, A., Wu, J., Hayes, M., Tang, Z., He, B., Liu, J. and Liu, M. (2014). Impact of meteorological drought on streamflow drought in Jinghe River Basin of China. *Chinese Geographical Science* 24(6): 694-705.

Zhou, J., Liu, Y., Guo, H.C. and He, D. (2014). Combining the SWAT model with sequential uncertainty fitting algorithm for streamflow prediction and uncertainty analysis for the Lake Dianchi Basin, China. *Hydrological Processes* 28: 521–533.