



**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**

**FK 2017 19**



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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**

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## **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

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**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<sup>2</sup>, 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 °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° N dan longitud 4.5– 7° E, adalah sebuah lembangan sungai merentas-sempadan yang merentas sembilan buah negara Afrika Tengah dan Barat dengan keluasan aktif berjumlah 925,796 km<sup>2</sup>, 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 °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 °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 biasanya 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.



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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!

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:

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## 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.

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## 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 °C and +6 °C 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.

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