MODELING IMPACTS OF CLIMATE CHANGE ON METEOROLOGICAL DROUGHTS DURING CROPPING SEASONS AND GROUNDWATER SUSTAINABILITY

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DEDICATION

To my Mother and my late Father

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ABSTRACT

Rising temperature and changing rainfall patterns due to global warming would change the frequency and severity of meteorological droughts. This change in climate would impact on several sectors particularly agricultural and water resources. Groundwater, protected from surface hydrological extremes is considered a reliable source to supplement water deficit during droughts and therefore, considered a valuable resource for climate change adaptation across the world. However, prolonged droughts may also affect groundwater resources and hence, it is critical to understand how droughts and groundwater resources will be affected by climate change in order to aid reliable planning of adaptation. The major objective of the present study is to model the impacts of climate change on meteorological droughts during crop growing seasons and groundwater sustainability using general circulation model (GCM) projections. Nigeria, one of the most vulnerable countries of the world to climate change was considered as the case study area. Considering scarcity of data, gauge based gridded rainfall data of global precipitation climatology centre (GPCC) and temperature data of climate research unit (CRU) for the period 1901-2010 and groundwater storage anomaly data of gravity recovery and climate experiment (GRACE) for the period 2002-2016 were used. The temporal variations in droughts estimated using standardized precipitation evapotranspiration index (SPEI) and their interrelations with rainfall and temperature trends were assessed using a 50-year moving window with a 10-year time step. The concept of reliability-resiliency-vulnerability (RRV) was used for the assessment of groundwater sustainability. Novel entropy based methods were used for selection of GCMs to reduce uncertainties in climate change projections. The performance of four state-of-the-art bias correction approaches was compared for selecting the best method for reliable downscaling of climate. Random Forest (RF) and Support Vector Machine (SVM) were used for the projection of groundwater storage anomaly due to climate change. Results revealed increase in drought severity for all the cropping seasons of Nigeria. Temperature was found to be the dominating factor for defining droughts in semi-arid regions in the north while rainfall influence dominates in the monsoon and tropical savanna zones in the south. Four GCMs namely MRI-CGCM3, HadGEM2-ES, CSIRO-Mk3-6-0 and CESM1-CAM5 were found to be the most suitable for the projection of rainfall and temperature in Nigeria. Future projection of rainfall and temperature using ensemble model for the period 2010 – 2100 revealed increase in annual maximum temperature in the range of 0 – 5.1^{o}C and changes in rainfall between 0 and 27.5% in rainy season. Maximum temperature was projected to increase more (3.5-5.1^{o}C) in the northwest and least (2.0-2.5^{o}C) in the south, while rainfall was projected to decrease up to 7.5% in the central and southern parts and increase up to 27.5% in north east. The study showed increase in droughts severity, frequency and affected area due to rises in temperature and changes in precipitation. Groundwater storage was projected to decline up to -12 m during rainy periods at some parts. Spatial assessment of changes in groundwater storage for future shows the northeast, southeast and south-south parts of Nigeria would mostly experience decrease in groundwater storage. Groundwater sustainability will be low in these areas and some other parts of the country for the future.

ABSTRAK

Kenaikan suhu dan perubahan pola hujan disebabkan oleh pemanasan global akan mengubah kekerapan dan tahap keterukan kemarau meteorologi. Perubahan iklim tersebut akan memberi impak kepada beberapa sektor terutamanya sektor pertanian dan sumber air. Air bawah tanah, yang terlindung daripada hidrologi permukaan yang ekstrem dianggap sebagai sumber yang boleh dipercayai untuk menambah defisit air semasa kemarau dan disebabkan itu, dianggap sebagai suatu sumber yang berharga untuk pengadaptasian perubahan iklim di seluruh dunia. Walau bagaimanapun, kemarau berpanjangan juga boleh menjejaskan sumber air bawah tanah dan dengan itu, adalah penting untuk memahami bagaimana kemarau dan sumber air bawah tanah akan terjejas oleh perubahan iklim bagi membantu perancangan adaptasi yang boleh diharap. Objektif utama kajian ini adalah permodelan kesan perubahan iklim terhadap kemarau meteorologi semasa musim tanaman dan kelestarian air bawah tanah menggunakan unjuran model peredaran umum (GCM). Nigeria, salah satu negara yang paling terdedah kepada perubahan iklim telah dipertimbangkan sebagai kawasan kajian kes. Disebabkan kekurangan data, data hujan bergrid berasaskan tolok oleh pusat iklim hujan global (GPCC) dan data suhu oleh unit penyelidikan iklim (CRU) bagi tempoh 1901-2010 serta data simpanan anomali air bawah tanah oleh pemulihan graviti dan eksperimen iklim (GRACE) bagi tempoh 2002-2016 telah digunakan. Variasi temporal dalam kemarau yang dianggarkan menggunakan indeks hujan sejat peluhan terpiawai (SPEI) dan hubungannya dengan tren hujan dan suhu telah dinilai menggunakan tempoh bergerak 50-tahun dengan langkah masa 10 tahun. Konsep kebolehpercayaan-kelangsungan-kerentanan (RRV) telah digunakan untuk penilaian kelestarian air bawah tanah. Kaedahberasaskan entropi baru digunakan untuk pemilihan GCM untuk mengurangkan ketidakpastian dalam unjuran perubahan iklim. Prestasi empat pendekatan pembetulan bias telah dibandingkan untuk memilih kaedah terbaik bagi iklim turun-skala yang boleh dipercayai. Hutan Rawak (RF) dan Mesin Vektor Sokongan (SVM) telah digunakan untuk unjuran simpanan anomali air bawah tanah disebabkan perubahan iklim. Keputusan mendedahkan peningkatan keterukan kemarau untuk semua musim menanam di Nigeria. Suhu didapati menjadi faktor yang dominan untuk mendefinisikan kemarau di kawasan-kawasan separa gersang di utara manakala hujan mendominasi di zon monsun dan tropika di selatan. Empat GCM iaitu MRI-CGCM3, HadGEM2-ES, CSIRO-Mk3-6-0 dan CESM1-CAM5 didapati paling sesuai untuk unjuran hujan dan suhu di Nigeria. Unjuran masa depan hujan dan suhu menggunakan model berkumpulan untuk tempoh 2010 - 2100 menunjukkan kenaikan suhu maksimum tahunan dalam lingkungan 0 - 5.1ºC dan perubahan hujan antara 0% dan 27.5% pada musim hujan. Suhu maksimum dijangka meningkat lebih banyak (3.5-5.1ºC) di barat laut dan kurang (2.0-2.5ºC) di selatan, manakala hujan dijangka menurun sehingga 7.5% di bahagian tengah dan selatan dan meningkat sehingga 27.5% di timur laut. Kajian menunjukkan peningkatan tahap keterukan kemarau, kekerapan dan kawasan yang terjejas berikutan kenaikan suhu dan perubahan hujan. Simpanan air bawah tanah dijangka berkurangan sehingga -12m semasa musim hujan di beberapa bahagian. Penilaian spatial terhadap perubahan dalam simpanan air bawah tanah untuk masa hadapan menunjukkan bahagian timur laut, tenggara dan selatan-selatan di Nigeria akan mengalami pengurangan dalam simpanan air bawah tanah. Kelestarian air bawah tanah akan menjadi rendah di kawasan-kawasan ini dan beberapa bahagian lain di negara di masa hadapan.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

AOGCM	Atmospheric Ocean Coupled Generation Circulation Model
BC	Bias Correction
CDF	Cumulative Distribution Function
CDI	Cumulative Departure Index
CF	Change Factor
CGPDA	China Gaige Based Daily Precipitation Analysis
CMIP3	Coupled Model Intercomparison Project Phase 3
CMIP5	Coupled Model Intercomparison Project Phase 5
CPC-Uni	Climate Prediction Center Unified
CRDC	Climate Reinfall Data Center
CRU	Climate Research Unit
DD	Dynamical Downscaling
DDM	Dynamical Downscaling Method
EG	Entropy Gain
EGS	Early Growing Season
ENSO	El Nini Southern Oscillation
GAQM	Gamma Quantile Mapping
GCM	Global Circulation Model
GDP	Gross Domestic Product
GEQM	General Quantile Mapping
GHCN	Global Historical Climatology Network
GHG	Green House Gases
GPCC	Global Precipitation Climatology Center
GR	Gain Ratio
GRACE	Gravity Recovery and Climate Experiment
IPCC	Intergovernmental Panel on Climate Change
ITCZ	Inter Tropical Convergence Zone
ITD	Inter Tropical Discontinuity
ITF	Inter Tropical Front
JICA	Japan International Cooperation Agency

LAM	Limited Area Models
LGS	Late Growing Season
LS	Linear Scaling
MI	Moisture Index
MK	Mann Kendall
m-MK	Modified Mann Kendall
MME	Multi Model Ensemble
MOS	Model Output Statistics
NCDC	National Climatic Data Center
NCEI	National Centers for Environmental Information
NOAA	National Oceanic and Atmospheric Administration
PCA	Partial Correlation Analysis
PCA	Principal Component Analysis
PDF	Probability Distribtuion Function
PP	Perfect Prognosis
PT	Power Transformation
QC	Quality Control
RAI	Rainfall Anomaly Index
RCM	Regional Climate Model
RCP	Representative Concentration Pathway
RF	Random Forest
SD	Statistical Downscaling
SDM	Statistical Downscaling Method
SPEI	Standardized Prescipitation Evapotranspiration Index
SPI	Standardized Prescipitation Index
SRES	Special Report on Emmision Scenarios
SU	Symmetrical Uncertainty
SVD	Singular Value Decomposition
SVM	Support Vector Machine
TDSI	Total Storage Deficit Indices
UDel	University of Delaware Research Center
WAM	West African Monsoon
WBG	World Bank Group

WCRP	World Climate Research Programme

LIST OF SYMBOLS

α - Scale
β - Shape
γ - Origin
$+$ - Positive
_ - Negative
% - Percentage
° - Degree
∞ - Infinity
$>$ - Greater than
$<$ - Less than

CHAPTER 1

INTRODUCTION

1.1 Background of the Study

The increased dynamics of the climate of the earth due to global warming is accompanied by tremendous shifts in the balance of its atmospheric system. The frequency and intensity of floods (Aich et al., 2016; Akter et al., 2018; Rojas et al. 2013; Nashwan et al., 2018), heat waves (Schar et al., 2004; McMichael et al., 2006; Khan et al., 2018a), droughts (Ahmed et al., 2015; Ward, 2014; Mohsenipour et al. 2018; Spraggs et al., 2015), ecosystem disturbances (Pérez-Ruiz et al., 2018; Wagena et al., 2018) among others are increasing or would increase across the globe due to these changes. The increases in climate related hazards subsequently may affect several sectors including water resources leading to water scarcity and economic losses, deterioration of social aspects of lives, health hazards leading to losses of lives, damages to agriculture causing several billions of dollars of destruction to crops, and the environment at large (Guhar-Sapir et al., 2016; Hinkel et al., 2013; Howitt et al., 2015). In addition, the ecosystem which is the most fragile part of the environment are being widely affected by droughts due to the changing climate (Bond et al., 2008; Corlett, 2016; Clark et al., 2017). These challenging impacts of global climate change would not decline in the near future, at least not until several decades of cutting down on greenhouse gases emission.

With continuous changes in the climatic variables and the effects they are having on our existence, understanding of the whole process from the causes to the changes that have occurred in the past to those that may happen in the future is crucial for preparation or mitigation of the impacts. The developing countries would be more affected by the impacts of climate change due to their lower adaptation capabilities (Abiodun et al. 2013, Collins et al. 2013). Most developing countries also have higher density of population with less awareness of climate change (Lee et al., 2015). This implies that a significant population of the world is at the risk of one or more form of the impacts of the changing climate.

Among natural disasters, droughts are critical and found to be more difficult to understand. They can occur due to increase in temperature, reduction of relative humidity, high winds, and precipitation timing and characteristics. Additionally, they can occur in both dry and wet climates (Mishra and Singh, 2010) and can be prolonged making their impacts very devastating. Droughts have become increasingly destructive in recent years in many parts of the world. For example, Brazil experienced its worst droughts in 80 years in 2014 (Freire - González et al. 2017). Some parts of the United States have experienced consecutive drought conditions between the years 2011 and 2016 with losses from agriculture running into several billions of dollars (NCEI, 2017). Three countries in Africa; Ethiopia, Kenya, and Somalia were battered by severe droughts between the years 2011 and 2012 leaving 13 million people affected and tens of thousands of lives lost (Slim, 2012).

Water scarcity is the major issue that results from the impacts of droughts on natural systems. Groundwater has the ability to compensate for the decreases in rainfall and increase in water demands that occur during droughts. Therefore in some countires in recent times, groundwater development is seen as a viable solution in combating scarcity of water due to increased severity and frequency of droughts induced by the changing climate. In line with this and due to the need of water for food security, countries are gradually directing focus to groundwater based irrigated agriculture. Some recent studies have however noted that groundwater resources would also face threats from climate change in the near future (Ranjan et al., 2006; Shahid et al., 2017; Salem et al., 2018; Kahsay et al., 2018). Precipitation pattern changes due to temperature rise will affect runoff (Cullen et al., 2002; Ionita et al., 2012), and consequently, the recharge of groundwater and its storage (Hanson et al., 2004; Holman et al., 2009; Venencio and Garcia, 2011; Tremblay et al., 2011; Perez-Valdivia et al., 2012). Decrease in soil moisture contents could also reduce recharge of groundwater and its availability as higher temperatures will increase evaporation and plant transpiration rates (Yu et al., 2015).

Understanding on-going changes and possible future changes in climate are essential components of adaptive capacity and necessary in the development of effective climate change adaptation policies (Batisani and Yarnal, 2010; Wang et al., 2016). Therefore, reliable assessment of the changes in droughts and groundwater resources due to climate change is very important for impact assessment and formulation of effective drought preparedness plans. However, availability of reliable data is the major obstacle in the quantification of the impacts of climate change in many parts of the world, particularly on the African continent. The suitability of gridded climate and hydrological data and robust methods for analysis of climate change impacts using limited data should be explored for hydro-climatic studies in data scarce regions.

1.2 Problem Statement

Climate change has serious potential impacts on the economic, environmental, social, and agricultural sector of any nation. Without doubt, water resources and the agricultural sectors which are the most important to human existence are among the mostly affected sectors by the changing climate. There have been several reports of the impacts of climate change on droughts in different parts of the world (Wilhemi and Wilhite, 2002; Piao et al., 2010; Ward, 2014; Byakatonda, 2018). The impacts of climate change on droughts have been assessed using various droughts indices. However, most of the studies didn’t assess droughts based on the cropping season in which droughts can be very destructive to crops (Alamgir et al., 2015; Mohsenipour et al., 2018). There is also a gap in research to understand the time varying changes in droughts characteristics during cropping season in order to understand their variability with time and identify the driving factors behind the changes in droughts.

General Circulation Models (GCMs) are generally used to simulate the present climate and project the future climate. However, a major challenge in projection of climate for impact assessment is the selection of appropriate set of GCMs (McSweeney et al., 2015; Salman et al., 2018). In practice, a small ensemble of appropriate GCMs is selected for the region of interest by excluding those that are considered unrealistic in order to reduce uncertainties associated with GCMs (Lutz et al., 2016; Pour et al., 2018; Khan et al., 2018b). A number of attempts have been made to assess the performance of climate models using different performance indices (Perkins et al., 2007; Masson and Knutti, 2011; Yokoi et al., 2011; Jiang et al., 2015a; Salman et al., 2018; Khan et al., 2018b). The major disadvantage of these performance indices is that they are based on the time-mean state of climate (Reichler and Kim, 2008) and thus, unable to capture the temporal variability of climate such as variation in the frequencies of climatic extremes which is equally important for the assessment of model performance. There is a need of finding more sophisticated approach for the ranking of GCMs and selection of ensemble of GCMs for projection of climate.

Due to their coarse resolutions, GCMs are generally downscaled into finer resolutions through either dynamical downscaling (DD) or statistical downscaling (SD) techniques for impacts assessment studies (Ahmed et al., 2018a). Statistical downscaling compared to dynamical are mostly preferred due to their flexibility, simplicity, computational speed, and provision of local scale information (Pour et al., 2014; Ahmed et al., 2015; Sachindra et al., 2014). There are two main subdivisions of the SD, the model output statistics (MOS) and the perfect prognosis (PP) (Maraun et al., 2010). The MOS method has the ability to account for errors that are inherent in GCMs (Turco et al., 2011; Eden and Widmann, 2014), making them widely applied in climate change projections (Eden and Widmann, 2014; Sunyer et al., 2015; Sa’adi et al., 2017; Bi et al., 2017; Shirvani and Landman, 2016; Moghim and Bras, 2017). There is always complexity in the relationship between local variables and GCM hindcasts, it is therefore important to explore the suitable approach that is sophisticated for this purpose in order to improve the downscaling performances and reliability in projection of climate.

Historical studies of droughts have shown their occurrences in many parts of the world (Sung and Chung, 2014; Ahmed et al., 2015; Zhang et al., 2017; Mohsenipour et al., 2018) including Nigeria (Oloruntade et al., 2017). Studies on future characteristics of droughts under a changing climate are also being conducted in different parts of the globe (Meza, 2013; Hernandez and Uddameri, 2014; Vu et al., 2017). However, most of the studies did not assess how the intensity, frequency, and areal extent of droughts are going to change during different cropping seasons under the different climate change scenarios. Besides, literature search shows while there are some studies on the projection of climate over Nigeria (e.g. Abiodun et al., 2013; Okoro et al., 2017), studies to assess the impacts of climate change on droughts during various crops growing seasons using CMIP5 have not been explored yet in this highly drought vulnerable region. The impacts of climate change on groundwater resources may affect its capability to offset large water demand during droughts (Wada et al., 2012; Pengra, 2012; Gandhi and Bhamoriya, 2011; Treidel et al., 2012). Groundwater resources are not very renewable in many areas including Nigeria (Macdonald et al., Kløve et al., 2014), and therefore may be faced with the devastating effects of climate change in the near future as predicted by some studies (Davidson and Yang, 2007; Ranjan et al., 2006; Treidel et al., 2012; Shahid et al., 2017). However, most of these studies did not assess how the changing climate is going to change sustainability of groundwater resources under different RCPs which is very important for areas where groundwater storages are declining due to climate change.

1.3 Research Objectives

The major objective of this study is to develop a methodological framework for the modeling of seasonal meteorological droughts and groundwater sustainability to assess the vulnerability of water resources in the context of climate change in Nigeria. The specific objectives of the study are:

i. To evaluate the historical changes in meteorological and groundwater droughts in Nigeria using gridded climate and terrestrial water storage data.

ii. To select an ensemble of GCMs for Nigeria based on their performances in simulating historical climate using entropy-based similarity assessment methods.

iii. To downscale and project the future changes in climate of Nigeria under different representative concentration pathways (RCPs) scenarios using state-of-the-art MOS approach.

iv. To assess the impacts of climate change on meteorological droughts and groundwater sustainability in Nigeria under different climate change scenarios.

1.4 Scope of the Study

This study mainly aimed to assess the impacts of climate change on meteorological droughts during crop growing seasons and sustainability in groundwater resources to understand the vulnerability of water resources under climate change scenarios. The developed framework in this study for modeling droughts and groundwater resources was tested through its application to the total area of Nigeria.

There are many gauged and satellite based gridded climate data that are used in place of observed data due to data scarcity. Amongst the commonly used gridded climate data are the Global Precipitation Climatology Center (GPCC) rainfall and Climate Research Unit (CRU) temperature data. These data were assessed and validated in this study for climate and hydrological modeling in Nigeria.

Different droughts indices, particularly standardized precipitation index (SPI) and standardized precipitation evapotranspiration index (SPEI) have been used for the identification and characterization of droughts. However, evapotranspiration which plays a significant role in semi-arid and arid regions incorporated into the SPEI method and thus, made it suitable for assessment of droughts in such environments. As a significant portion of Nigeria is arid and semi-arid, SPEI was adopted for assessing the changing characteristics of meteorological droughts for the entire country.

For the future assessment of the impacts of climate change on droughts and groundwater resources, the CMIP5 GCM simulations are used. Among the pool of GCMs of the CMIP5, 20 models were selected for Nigeria based on their availability of simulation for all the representative concentration pathways (RCPs). Of these, few highest performing models were selected and aggregated into an ensemble rainfall and temperature model based on their performances using a number of criteria.

The impacts of the changing climate on water resources were assessed from the changing characteristics of rainfall and temperature and by using gridded Gravity Recovery and Climate Experiment (GRACE) terrestrial water storage data in assessing the past, present, and future changes in groundwater for Nigeria.

Various parametric and non-parametric methods were used in the study for the assessment of trends. Empirical models were developed using data mining methods and were compared based on their performances for the assessment of the changes in climate and groundwater storage.

1.5 Significance of the Study

Among natural disasters, droughts are most difficult to understand. Droughts can be very devastating due to their prolonged periods of occurrence and their extent and intensity of occurrences. Furthermore, their occurrences during crop growing season are more ravaging, causing severe damages to agricultural crops, thereby, resulting in large economic losses or famine. A methodology is proposed in this study for the assessment of time varying properties of droughts for understanding the factors responsible for the changes in droughts. The method can be used in any other regions for systemic assessment of changing characteristics of droughts during different periods due to climate change.

The methodological framework developed in this study will be invaluable for the assessment and validation of GCM simulation in order to provide more confidence in their use for the assessment of the changing characteristics of droughts. The selection of an ensemble of GCM will reduce the uncertainties associated with individual GCMs for climate projections.

The methods proposed for downscaling of the rainfall and temperature will give a confidence in climate projections. The downscaled climate for Nigeria would provide insights into the future changing characteristics of climate variables which may be used in understand their impacts on various natural systems. This will be significant in developing appropriate adaptation plans and preparedness, prevention and mitigation measures against global environmental changes.

A comprehensive understanding of the historical droughts during crop growing seasons will be significant in understanding the spatial and temporal trends in droughts which can be useful in understanding droughts progression over time. The use of easily available gridded data would make the method used for drought assessment in this study replicable in any other regions of the globe including areas where climate data are scarce.

The changing climate is changing the spatial and temporal patterns of climate variables especially rainfall and temperature. These changes are increasingly aggravating the frequencies and intensities of disasters. Nigeria, like many other countries of the globe is struggling with the impacts of the changing climate. Intermittent years of droughts and increasing droughts in some areas of the country due to increasing temperature are occurring. It has been projected that droughts in Africa will be more devastating in the future due to its location in a drought prone area. For a country like Nigeria with a significant population depending on rain-fed agriculture, and experiencing continuous increase in population, it is required to boost its sustainability in natural resources. The findings of the study can be used for climate change adaptation planning to mitigate the impacts of climate change on agriculture and water resources for sustainable development.

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