African Journal of Environmental Science and Technology Vol. 5(10), pp. 760-768, October 2011
Available online at http://www.academicjournals.org/AJEST
DOI: 10.5897/AJEST11.081
ISSN 1996-0786 ©2011 Academic Journals

Review

Potential impacts of climate change and variability on groundwater resources in Nigeria

A. P. Aizebeokhai

Department of Physics, Covenant University, Ota, Ogun State, Nigeria.
E-mail: philips.aizebeokhai@covenantuniversity.edu.ng.

Accepted 28 September, 2011

Climate change observed over the past decades has been consistently associated with modifications of components of the hydrological systems such as precipitation patterns, sea surface temperature, accelerated melting of glacier and ice caps, soil temperature and moisture, surface runoff and stream flow. Such changes are known to influence subsurface hydrological systems, which could lead to changes in groundwater recharge, discharge and storage of many aquifers. Although, there are uncertainties in the characterisation of climate change induced groundwater impacts due to largely multi-scale local and regional heterogeneity, there is need to evaluate groundwater resources, quality and vulnerability to climate change and variability. This paper attempts to assess the potential impacts of climate change and variability on groundwater resources availability and sustainability in Nigeria.

Key words: Climate change, variability, hydrological systems, groundwater, potential impacts, vulnerability.

INTRODUCTION

All life on Earth, water and energy resources, agriculture, vegetation, air quality and sea level are significantly influenced by climate change and variability (US Geological Survey, 2007). Geologically, life has existed on planet Earth for approximately four billion years. During this time, climate has swung between ice ages and warm periods. The Earth's atmosphere has generally been in chemical balance. The increasing global demand for energy and natural resources to meet the need of the ever growing population is believed to be upsetting this atmospheric balance (Warner, 2007), and thus giving rise to climate change. Various studies by the Intergovernmental Panel on Climate Change (IPCC) suggest a discernible human influence on global climate change. Thus, climate change and variability has received increased global attention in the last three decades. This is largely due to the risk it poses to the environment and hence the global community.

According to IPCC, climate change is a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods (Bates et al., 2008). Climate variability, on the other hand, refers to variations in the mean state and other statistics (such as standard deviations, the occurrence of extremes, etc.) of the climate on all spatial and temporal scales beyond that of individual weather events. Climate variability may be due to natural internal processes within the climate system (internal variability), or to variations in natural or anthropogenic external forcing (external variability). Huge information and knowledge gap on climate change and variability, as well as the potential impacts still exist in most part of Africa. Nigeria is widely recognized to be vulnerable to climate change and variability.

Groundwater, one of the most important natural resources globally, is an important part of the global freshwater supply. Globally, groundwater provides much of the public and domestic water supply, supports agricultural and industrial economies, and contributes its flow to rivers, lakes and wetlands; and this helps in maintaining a balance in the ecosystem. Groundwater is the primary source of potable water in most part of Nigeria, particularly in rural areas which rely on low-cost domestic (private) boreholes and/or hand-dug wells. The situation is the same in most rural population around the world. Groundwater also influences the design and constructions of many engineering facilities such as dams, roads, rails, subways, waste disposal sites, high rise buildings, etc. The long-term viability of dams is

Figure 1. Relief map of Nigeria.

influenced by groundwater flow under or around the dam. The vulnerability of this important resource to climate change and variability has not been adequately studied, especially in developing countries like Nigeria where the development and withdrawal of groundwater is largely uncontrolled. Thus, there is need for proper understanding of the potential impacts of climate change and variability on groundwater resource availability and sustainability. This paper attempts to assess the potential impacts of climate change and variability on groundwater resources availability and sustainability in Nigeria.

CLIMATE AND RELIEF

Nigeria, bordered by Republic of Benin in the west, Cameroon in the east and the Gulf of Guinea in the south (Figure 1), is situated in the West Africa sub region and covers a land mass of about 911,000 square kilometres. Its terrain is very variable but predominantly with mountains in the southeast, hills and plateau including Jos Plateau in the centre, lowlands in the south and plains in the north. The highest point is Chappal Waddi with an elevation of 2419 m in eastern Nigeria and the lowest point is sea level in the south (British Geological Survey, 2003).

As in most part of West Africa, Nigeria's climate is characterized by strong latitudinal zones, varying from equatorial in the south to tropical in the centre and arid in the north. Rainfall is the key climatic variable, and is seasonal with a wet season occurring between July to September in the north, extending to April and November in the south. Annual rainfall varies from over 4000 mm in the south to less than 250 mm in the north, with an annual mean of about 1180 mm. Two air masses control rainfall – moist northward-moving maritime air coming from the Atlantic Ocean and dry continental air coming south from the African landmass. Topographic relief plays a significant role in local climate only around the Jos Plateau and along the eastern border highlands.

Temperatures are generally high throughout Nigeria; diurnal variations are more pronounced than seasonal ones. Highest temperatures occur during the dry season; rains and moderate afternoon highs occur during the wet season. The variation of average temperatures from coastal to inland areas is quite small. Inland areas, especially in the northeast, have greater extremes with temperatures as high as 44°C before the onset of the rains and as low as 6°C during an intrusion of cool air from the north between December and February.

Vegetation largely follows the climatic variation, with densely vegetated mangrove swamps in the south, tropical rainforest in the centre, through to savannah in the north and Sahel savannah in the extreme north-east.

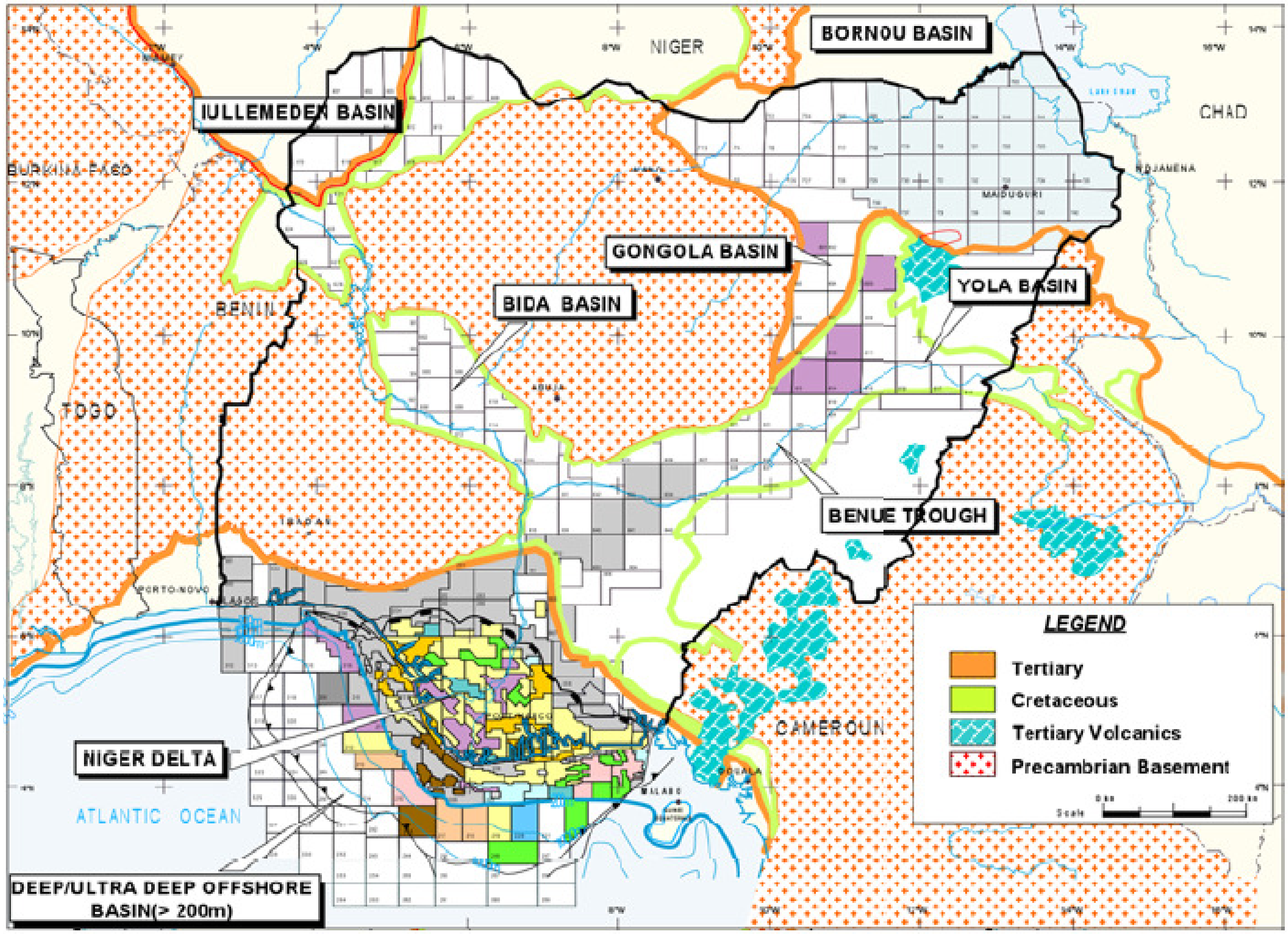

Figure 2. Geological map and sedimentary basins of Nigeria.

With a population of about 150 million people, Nigeria is the most populous country in Africa. It is presently composed of 36 states beside the capital city, Abuja (Figure 1). Nigeria is drained majorly by River Niger which flows from the north-west of the country southward to the Niger delta. The principal tributary of River Niger is the Benue River which runs south-westwards and joins the Niger at Lokoja (Figure 1). Other important rivers are the Cross River in the south and Imo River in the south-east. Lake Chad, the largest freshwater lake in Africa, lies to the north-east of the Nigerian border and its drainage basin occupies about 20% of the nation's land area. Other bodies of surface water in the arid north-east include a number of small lakes and playas, some of which are saline.

GEOLOGY

Ancient Precambrian basement rocks, deformed during the Pan African orogeny, occupy about half the land mass of Nigeria, outcropping in the west (Lokoja–Abeokuta–Babana), south-east (plateau bordering Cameroon) and north-central (Bauchi–Kano–Anka–Kontagora) areas (Figure 2). The basement rocks are mostly metasediments (gneisses, schists, migmatites and calc-silicates) along with amphibolites and rarer metamorphosed tuffs and volcanic rocks. The basement also consists of banded iron formations, rich in magnetite and haematite, with the most prominent outcrops in south-east of Kabba, southern Nigeria. Precambrian granitic intrusions are common in the basement areas (Wright, 1985). Younger granites and associated minor intrusions of Jurassic age form a large part of the Jos Plateau of central Nigeria, and are often associated with tin (cassiterite) mineralisation. Tertiary volcanic rocks, basalts and rhyolites, occur sporadically above basement rocks on the Jos Plateau and the eastern plateau areas (British Geological Survey, 2003).

Mesozoic and younger sediments cover the remaining parts of Nigeria (Figure 2) and these are located in a number of sedimentary basins, comprising the Benue (central), Sokoto (north-west border), Chad (north-east), Bida (central, along the Niger valley), Dahomey (south-west) and Anambra (south-east) Basins and the Niger delta (south coastal). The Benue Basin is a large elongate rifted basin running along the approximate line of the Benue River. The basin is in-filled with about 5000 m of Cretaceous sediment overlying crystalline basement rocks. Sediment thickness increases southwards in response to basin subsidence. Oldest Cretaceous sediments of the Benue Basin include marine black shales, often carbonaceous and pyrite-rich, in the lower part of the basin (south). Coarser grained sediments which are fluvial-deltaic sandstones with occasional shale intercalations and conglomerate horizons dominate in the upper part of the basin (Wright, 1985). The Bida Basin, aligned north-west to south-east passing through Bida to Auna, is a shallow un-faulted extension of the Benue Basin. Conglomerates and pebbly sandstones with clay lenses are predominant in the Cretaceous sequence of the Bida Basin. Ironstones, best developed in the Agbaja Plateau near Lokoja, are also present in the basin. The sediments reach up to 1000 m in thickness in some parts of the basin. The Sokoto Basin in the north-west is dominated by Tertiary marine clays, while Tertiary and Quaternary (Chad Formation) clay-rich sands and sandstones, about 700 m thick, dominate the sequence of the Chad Basin in the north-east (British Geological Survey, 2003).

The Niger delta in south has been prograding outwards to the Atlantic Ocean since late Cretaceous times and is in-filled with Tertiary and Quaternary sediments which decreases in age progressively southwards. The deposits comprise from north-east to south-west, the Imo Shale, a unit of Palaeocene to Eocene blue-grey shales with thin sandstones and limestones; the Eocene to Oligocene Ameki Formation, comprising clays, sandstones and limestones; Oligocene to Miocene clays, sands and grits with occasional lignite of the Ogwashi-Asaba Formation; and the Miocene to Pliocene Benin Formation composed of coastal-plain sands and pebbly sands with clay lenses and lignite. In all, the sediments reach a maximum thickness of about 12,000 m and show an upward transition from marine pro-delta shales (Akata Formation) through a paralic interval (Agbada Formation) to a continental sequence (Benin Formation). The formations are strongly diachronous (Haack et al., 2000) and cut across the time stratigraphic units which are characteristically S-shaped in cross-section. Most economically exploitable hydrocarbon in the delta is believed to be trapped within the Agbada Formation.

GROUNDWATER RESOURCES AVAILABILITY

Groundwater constitutes an important source of fresh water supply for domestic, industrial and agricultural purposes in Nigeria. The sedimentary basins (Figure 2) generally form the principal aquifers. The Sokoto Basin in the north-west, which is part of the vast Iullemenden Basin of Mali, Niger and Algeria, consists of major confined and unconfined aquifers. Typically, the depth to water table in the unconfined parts range from 15 to 75 m. Artesian conditions occur in confined aquifers at 75 to 100 m depth at the eastern edge of the basin; however, the piezometric levels are usually about 50 m depth further west (UN, 1988). Three main aquifers consisting of an upper aquifer at 30 to 100 m depth, a middle aquifer (eastern part of the basin) some 40 to 100 m thick occurring from 230 m depth near Maiduguri and a lower aquifer consisting of 100 m of medium to coarse sands and clays occurs at a depth of 425 to 530 m are known in Chad Basin. The upper and middle aquifers are exploited intensively in the Maiduguri area (UN, 1988). Recent decline in groundwater levels in the Chad Basin is believed to be due to over-exploitation of the aquifers in the basin. This has necessitated drilling to greater depths in order to tap the lower aquifer.

Further south, sediments in the Benue Basin are often fine-grained and thus, constitute low yield aquifers. Most of the aquifers in the basin are unconfined, but confined conditions occur locally in the Yola-Numan area. The Cretaceous sandstones of the Bida Basin form good aquifers with significant groundwater resources. In the Anambra Basin, coarse Cretaceous sandstones form good aquifers. These aquifers are largely unconfined in the northern part but become artesian further south with groundwater levels typically about 60 to 150 m deep. Good aquifers are also present in the Tertiary and Quaternary sediments of coastal areas down south, the best being the Tertiary 'Illaro Formation' composed of sands with occasional beds of clay and shale. Shallow unconfined aquifers are common at depth less than 30 m in most part of the coastal and near-coastal area.

Unlike the sedimentary aquifers, groundwater storage in the crystalline basement is small and largely limited to fracture zones and areas of deep weathering. The weathered overburden layer overlying crystalline basement rocks can be thick in some part of the basement complex. Hand-dug wells form the principal source of groundwater in most part of the basement complex. The country's shallow aquifers are potentially vulnerable to pollution from agricultural (fertilisers), domestic (waste dumps, latrines) and industrial sources, except where surface layers are of poor permeability and afford some protection of the underlying aquifers. Groundwater in the alluvial aquifers is usually fresh; however, high salinity related to dissolution of evaporate minerals have been recognised in some cases. High concentrations of iron and manganese are common in confined aquifers. The presence of hydrogen sulphide in some aquifers is also reported in parts of the Benue Basin. Over-withdrawal of groundwater from parts of the

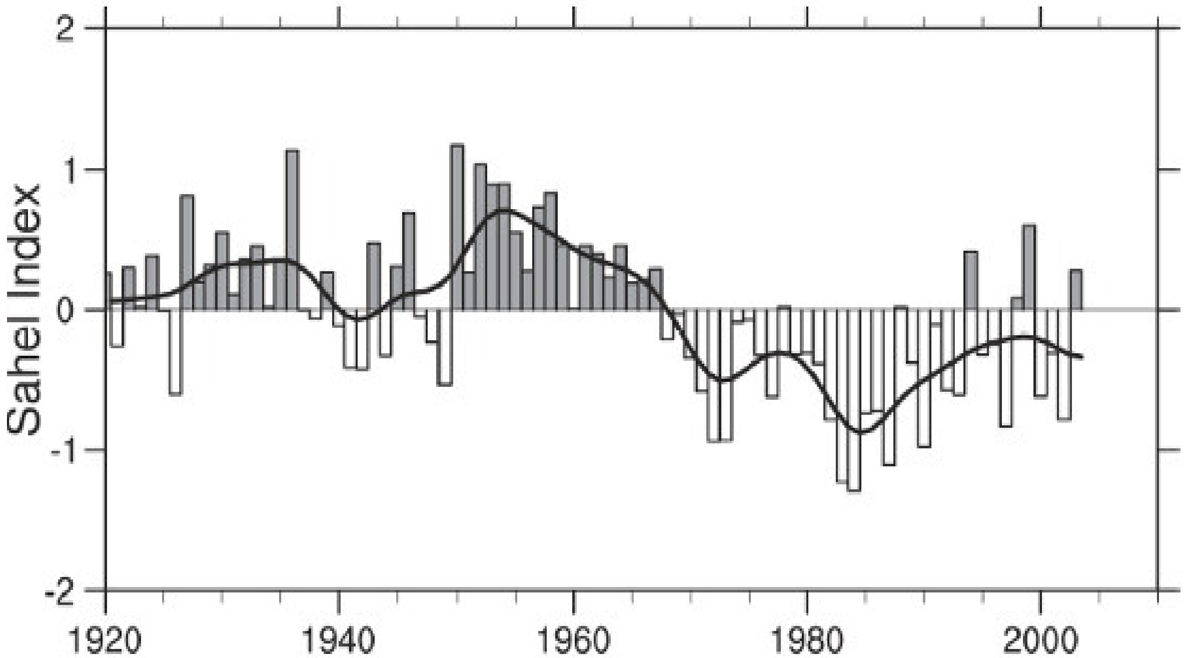

Figure 3. Normalised rainfall index for the Sahelian region of West Africa (after Bates et al., 2008).

coastal aquifers can potentially led to the problem of saline-water intrusions, particularly in Lagos, Delta and Rivers States. In the arid northern areas, over-withdrawal of groundwater for irrigation can cause salinization of shallow aquifers through the long-term effects of evapotranspiration (British Geological Survey, 2003).

OBSERVED AND PROJECTED CHANGES IN CLIMATE RELATED TO WATER RESOURCES

Analysis of the routine measurements of the Earth's surface temperature reported daily from thousands of weather stations across the globe, both on land and at sea, suggests that the surface of the Earth has warmed considerably over the last 150 years. Apart from the increase in the global air and ocean temperatures, many scientific studies indicate accelerated melting of glacier and ice caps; rising sea levels, changes in ocean salinity and wind patterns; wide spread changes in amount of precipitation; and increased occurrence of extreme weather conditions, including droughts, heavy precipitation, heat waves and intensity of tropical cyclones. These changes in climate which occur in multiple time scales have been largely attributed to human activities on Earth, particularly the emission of green house gases. Also, natural processes often lead to climate variability that occur on all time scales across the Earth ranging from inter-annual, multi-decadal, and longer geologic-time scales. This constitutes a major obstacle to the reliable characterization of global climate change resulting from human activities (Ghil, 2002).

The hydrological cycle is intimately linked with changes in atmospheric temperature and radiation balance. Climate change indicators observed over the past several decades has been consistently associated with modifications in a number of components of the hydrological systems (Sherif and Singh, 1999; Milly et al., 2005; Bates et al., 2008). Some of these climate indicators include changing precipitation patterns, accelerated melting of glaciers and ice caps, increasing evaporation, changes in soil temperature moisture, and changes in surface runoff and stream flow. An example of the large-scale regional and persistent trend in precipitation in West Africa, which has occurred over the last 80 to 90 years, is given in Figure 3. Such changes to the surface components of the global hydrologic cycle will likely influence the subsurface hydrological systems within the soil, unsaturated (or vadose) zone, and saturated zone. This could likely lead to changes in groundwater recharge, discharge and storage of many aquifers.

There is significant natural variability in all components of the hydrological systems on inter-annual to decadal time-scales. This multi-scale variability in all components of the hydrological systems often masks long-term climate change induced trends. However, there exist substantial uncertainties in the characterization of climate change induced trends of hydrological variables due largely to local and regional differences and limitations. Understanding climate change and variability is vital for society and ecosystems, particularly with regard to

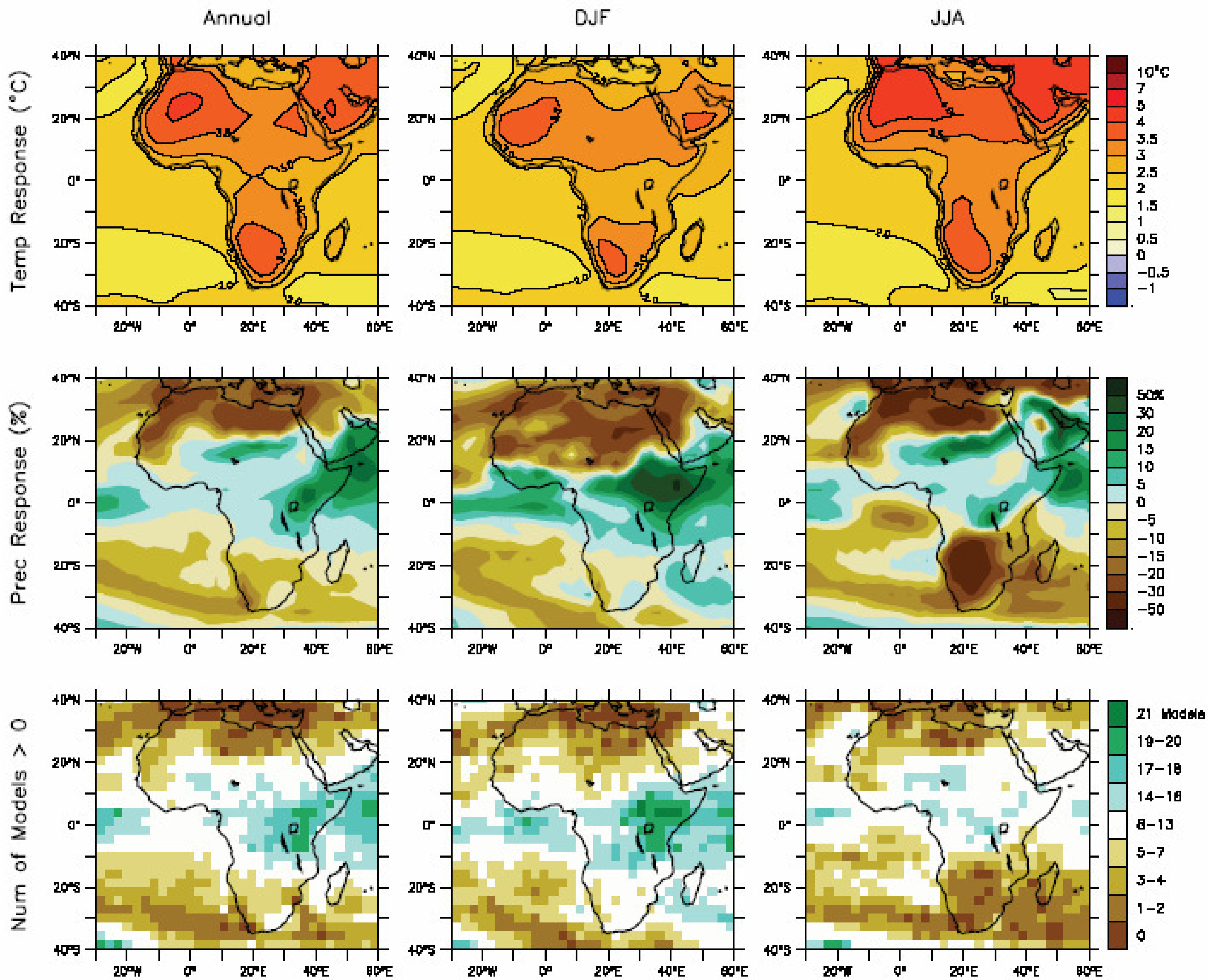

Figure. 4. Temperature and precipitation changes over Africa from the MMD-A1B simulations. Top row: Annual mean, winter (DJF) and summer (JJA) temperature change between 1980-1999 and 2080-2099, averaged over 21 models. Middle row: same as top, but for fractional change in precipitation. Bottom row: number of models out of 21 that project increases in precipitation (Source: Christensen et al., 2007).

complex changes affecting the availability and sustainability of surface-water and groundwater resources (US Geological Survey, 2009).

Climate model simulations for the 21st century are consistent in projecting increased precipitation in high latitudes and parts of the tropics, and decreased precipitation in some subtropical and lower mid-latitude regions (Bates et al., 2008). The MMD-A1B simulation projections for temperature and precipitation changes over Africa are given in Figure 4. Sub-Saharan Africa is projected to witness increased precipitation, though with high degree of uncertainties. The projected increased in precipitation is attributed to the projected increased in warming over the projected global average for West Africa. Heavy precipitation events are projected to become more frequent over most parts of the region. High variability in precipitation is also expected to be more common in the region. The Savannah and Sahel regions, which currently suffers from seasonal and inter-annual climate variability, are projected to witness decreasing and highly variable precipitation coupled with increasing temperature/warming. This region is also projected to be affected by more droughts with increasing desertification.

By the middle of the 21st century, annual average river runoff is projected to increase at high latitudes and in some wet tropical areas, and decrease over some dry regions at mid-latitudes and in the dry tropics. Many semi-arid and arid areas are projected to suffer a decrease of water resources (including groundwater) due to climate change. These projected changes in runoff largely mimic the projected changes in precipitation. Increased precipitation intensity and variability is projected to increase the risks of flooding in many coastal areas, and drought in many arid and semi-arid regions. Higher water temperatures and changes in extremes, including floods and droughts, are projected to affect water quality and exacerbate many forms of water pollution.

POTENTIAL IMPACT OF CLIMATE CHANGE ON GROUNDWATER RESOURCES

Understanding climate change and variability is vital for society and ecosystems. The complex changes (Dragoni and Sukhija, 2008) affecting the availability and sustainability of surface-water and groundwater resources are particularly important. The impacts of climate change and variability on water resources are well recognized globally and have been identified as a major issue facing the availability of fresh water (including groundwater) resources. The availability and sustainability of groundwater in many aquifers in Nigeria, like many principal aquifers around the world (US Geological Survey, 2009; Brekke et al., 2009; Alley et al, 2002), may be under threat in the next few decades because of depletion of the resource imposed by human and climatic stresses. In particular, the fringes of northern Nigeria characterised to be under stress due to droughts and variability in precipitation is likely to witness severe aquifer depletion. The hidden nature of groundwater resources often result in development and exploitation that is largely uncontrolled, especially in developing countries and this can result in over-exploitation and contamination of groundwater. Thus, even without considering climate change and variability, groundwater sustainability is a major challenge because groundwater resource is affected by a number of factors.

Many scientific studies have helped to improve the understanding of the effects of climate change and variability on fresh water resources. However, most of the researches have focused primarily on surface water because of its visibility, accessibility, and the more obvious recognition of the effects of climate change and variability on surface water than on groundwater (US Geological Survey, 2009). Recent research efforts are focused more on understanding the effects of climate change and variability on groundwater resources availability, sustainability and quality; but these effects remain poorly understood (Green et al., 2007a, b).

The potential effects of climate change and variability on groundwater are more complex to understand than its effects on surface-water (Holman, 2006). Groundwater-residence times can range from days to tens of thousands of years or more. This could possibly delay and disperse the effects of climate change and variability on groundwater; and thus, efforts to detect responses of groundwater to climate change and variability are often very challenging (Chen et al., 2004). In addition, human activities, such as groundwater extraction and the resulting loss of storage and capture of natural discharge, are often on the same time scales as some variable of climate change and variability. This makes it difficult to distinguish between human induced stresses and climatic stresses on groundwater. For example, the magnitude and phase relation of El Nino/ Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO), and Atlantic Multi-decadal Oscillation (AMO) cycles may result in average or extreme climatic conditions that may significantly influence drought, infiltration, recharge, discharge, and demand for groundwater resources.

Basically, climate change and variability affects groundwater recharge rate, depth to water table and water levels in aquifers. The projected increase in precipitation variability, both in intensity and frequency, is most likely to lead to decrease in recharge in most part of southern Nigeria. This is because frequent and heavy precipitation results in reduced infiltration capacity of the soil. Also, the projected increase in precipitation would result to increased recharge in some part of the semi-arid northern Nigeria because high intensity precipitation is able to infiltrate high enough before evaporating. The projected decrease in precipitation and increasing droughts in the Savannah and Sahel regions would lead to decrease in groundwater recharge and this will results to increasing desertification. In general, most simulated models for climate change and variability predicted more than 70% decrease in recharge for south-western Africa by 2050. Thus, groundwater stress would be more severe in most part of West Africa by 2050.

In addition, increased in precipitation and changes in extremes, including floods and droughts would result to increased erosion and deterioration of groundwater quality which would exacerbates many forms of water pollution, particularly in southern Nigeria. This is because more sediment, nutrients, dissolved organic matter, pathogens, heavy metals, pesticides and salts are likely to infiltrate many aquifers more rapidly. This pollution has potential negative impacts on human health, ecosystems, and water system reliability and operating cost. In areas with shallow water table, increased recharge would lead to increased soil salinization and waterlogged soils and this can damage urban and agricultural areas. Sea-level rise may extend areas of saline-water-intrusion and estuaries in most coastal aquifers and this would results in decreased freshwater availability for human and ecosystems.

Increasing depth to water table and declining recharge will jeopardise many wetlands dependent on aquifers; and base flow runoff in streams during dry seasons will be reduced. Increased precipitation extremes would also results to increased coastal erosion in southern Nigeria. The cost for groundwater development and water supply would increase in most part of the country. Access to potable water would be more difficult in areas with declining recharge as well as increasing groundwater pollution. Extremes changes in the quality and quantity of groundwater, particularly in the unsaturated (vadose) zone, are expected to have adverse effects on food availability, stability, access and utilization. This would results to decreased food security and increased vulnerability of poor rural farmers, especially in arid and semi-arid regions (IPCC, 2007; Bates, 2008). Thus, the impacts of climate change and variability particularly on water resources constitutes a major threat to development and the achievement of the Millennium Development Goals (MDGs), especially with goals relating to poverty eradication and mortality rate.

Recent research efforts have characterized subsurface hydrologic and geochemical responses to climate change and variability on inter-annual to multi-decadal time scales. Variability on these time scales has the most tangible implications for groundwater resource management (Hanson et al., 2006, 2009; Hanson and Dettinger, 2005; Gurdak et al., 2007). Climate variability on these time scales is often the result of ENSO, PDO, and AMO and can have substantial influence on recharge, discharge, and water-table fluctuations in many aquifers. Response of groundwater levels can be striking when climate variability from ENSO, PDO, and AMO are coincident in a positive or negative phase of variability. The observed irregular variations in the time series of hydrological variables such as precipitation, air temperature, stream flow, and groundwater levels is a reflection of a range of natural and human climate stresses (Hanson and Dettinger, 2005).

Available evidences from observational records and climate projections indicate that freshwater resources including groundwater are vulnerable to climate change and variability. The ability to quantify future changes in hydrological variables and their impacts on groundwater systems is currently limited by uncertainties at all stages of the assessment process (Huntington, 2006). The uncertainties are largely due to the range of socio-economic development scenarios and climate model projections for a given scenario, downscaling of climate effects to local/regional scales, impact assessments, and feedbacks from adaptation and mitigation activities. Information about groundwater-related impacts of climate change and variability is inadequate, especially with respect to groundwater quality and ecosystems, and the socio-economic dimension of the impacts. There has been little or no research on the impacts of climate change and variability on groundwater resources in Nigeria. Thus, more researches on the influence of climate change and variability on groundwater vulnerability as well groundwater-surface water interaction are required. This would improve our understanding and modelling of climate changes related to hydrological cycles at scales relevant to decision making.

CONCLUSION

Groundwater is an important part of the global freshwater supply that may be largely vulnerable to climate change and variability. A proper understanding of the potential impacts of climate change and variability on groundwater resource availability and sustainability is therefore crucial. An understanding of climate change and variability can be integral to successful management of groundwater resources. Thus, there is a need to evaluate and understand climate change and variability over long term for better planning and management of groundwater resources. The increasing stresses on groundwater resources from population growth and industrial, agricultural, and ecological needs should be taken into consideration in the management of groundwater resources. Current tools to facilitate integrated appraisals of adaptation and mitigation options across multiples water-dependent sectors are inadequate. More research on the influence of climate change and variability of hydrological variables is required so as to improve our understanding and modelling of climate changes related to hydrological systems at scales relevant to decision making.

Concerted efforts should be made to address the following critical questions relating to the potential impacts of climate change and variability on groundwater resources: how do groundwater recharge, discharge, and change in storage in principal aquifers respond to climate change and variability on inter-annual to multi-decadal time-scales; are there certain principal aquifers that are more or less susceptible to changes in storage due to climate change and variability; what trends in groundwater quality can be linked to climate change variability; what strategic role will groundwater storage play in adapting to climate change and variability; and what policies can we put in place to facilitate monitoring of groundwater depletion, recharge, quality and use?

REFERENCES

Alley WM, Healy RW, LaBaugh JW, Reilly TE (2002). Flow and storage in groundwater systems. Science, 296(5575): 1985–1990.

Bates BC, Kundzewicz ZW, Wu S, Palutikof JP, Eds. (2008). Climate Change and Water. Technical Paper of the Intergovernmental Panel on Climate Change, IPCC Secretariat, Geneva, 210 p.

Brekke LD, Kiang JE, Olsen JR, Pulwarty RS, Raff DA, Turnipseed DP, Webb RS, White KD (2009). Climate change and water resources management – A federal perspective. U.S. Geol. Surv. Circ., 1331: 65 .

British Geological Survey (2003). Groundwater quality: Nigeria. NERC, pp. 1-9.

Chen Z, Grasby S, Osadetz K (2004). Relation between climate variability and groundwater levels in the upper carbonate aquifer, southern Manitoba. Canada J. Hydrol., 290: 43–62.

Christensen JH, Hewitson B, Busuioc A, Chen A, Gao X, Held I, Jones

R, Kolli RK, Kwon WT, Laprise R, Magaña RV, Means L, Menéndez CG, Räisänen J, Rinke A, Sarr A, Whetton P (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, in Solomon, S, Quin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL, (eds.), Cambridge University Press, Cambridge.

Dragoni W, Sukhija BS (2008). Climate change and groundwater - A short review. In Dragoni W, Sikhija BS, eds., Climate change and groundwater. London, Geol. Soc. Spec. Public., 288: 1–12.

Ghil M (2002). Natural climate variability, in MacCraken MC, Perry JS, eds., Encyclopedia of global environmental change, Vol. 1, The Earth system: Physical and chemical dimensions of global environmental change. Chichester, John Wiley and Sons, pp. 544–549.

Green TR, Bates BC, Charles SP, Fleming PM (2007a). Physically based simulation of potential effects of carbon dioxide: Altered climates on groundwater recharge. Vadose Zone J., 6(3): 597–609.

Green TR, Taniguchi M, Kooi H (2007b). Potential impacts of climate change and human activity on subsurface water resources. Vadose Zone J., 6: 531–532.

Gurdak JJ, Hanson RT, McMahon PB, Bruce BW, McCray JE, Thyne GD, Reedy RC (2007). Climate variability controls on unsaturated water and chemical movement. High plains aquifer, USA. Vadose Zone J., 6: 533–547.

Haack RC, Sundararaman P, Diedjomahor JO, Xiao H, Gant NJ, May ED, Kelsch K (2000). Niger Delta petroleum systems, Nigeria. In Mello MR, Katz BJ, eds., Petroleum systems of South Atlantic margins. Am. Assoc. Petrol. Geol. Memoir, 73: 213-231.

Hanson RT, Dettinger MD (2005). Ground water/surface water responses to global climate simulations, Santa Clara–Calleguas Basin, Ventura, California. J. Am. Water Resour. Assoc., 41(3): 517-536.

Hanson RT, Dettinger MD, Newhouse MW (2006). Relations between climatic variability and hydrologic time series from four alluvial basins across the southwestern United States. Hydrogeol. J., 14(7): 1122-1146.

Hanson RT, Izbicki JA, Reichard EG, Edwards BE, Land MT, Martin P (2009). Comparison of ground-water flow in southern California coastal aquifers. In Lee HJ, Normark B, eds., Earth sciences in the urban ocean – The southern California continental borderland. Geol. Soc. Am. Spec., 454: 345–373.

Huntington TG (2006). Evidence for intensification of the global water cycle: Review and synthesis. J. Hydrol., 319: 83–95.

Holman IP (2006). Climate change impacts on ground-water recharge: Uncertainty, shortcomings, and the way forward. Hydrogeol. J., 14(5): 637-647.

Intergovernmental Panel on Climate Change (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 [Core Writing Team, Pachauri RK, Reisinger A (eds.)]. IPCC, Geneva, Switzerland, 104 p.

Milly PCD, Dunne KA, Vecchia AV (2005). Global pattern of trends in stream flow and water availability in a changing climate. Nature, 438(7066): 347–350.

UN (1988). Ground Water in North and West Africa. Natural Resources/Water Series, 18, United Nations, New York.

US Geological Survey (2009). Effects of climate variability and change on groundwater resources in the United States: US Geological Survey. Fact Sheet, 304: 4.

US Geological Survey (2007). Climate variability and change: US Geological Survey. Fact Sheet, 3108: 2.

Sherif MM, Singh VP (1999). Effect of climate changes on seawater intrusion in coastal aquifers: Hydrol. Process., 13(8): 1277–1287.

Warner SD (2007). Climate change, sustainability, and ground water remediation: The connection. Ground Water Monit. Remed., 27(4): 50–52.

Wright JB (1985). Geology and Mineral Resources of West Africa. Allen & Unwin, London, 187 p.