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Challenges in water resources of Lagos mega city of Nigeria in the context of climate change

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ABSTRACT

This study assesses the water resources and environmental challenges of Lagos mega city, Nigeria, in the context of climate change. Being a commercial hub, the Lagos population has grown rapidly causing an insurmountable water and environmental crisis. In this study, a combined field observation, sample analysis, and interviews were used to assess water challenges. Observed climate, general circulation model (GCM) projections and groundwater data were used to assess water challenges due to climate change. The study revealed that unavailability of sufficient water supply provision in Lagos has overwhelmingly compelled the population to depend on groundwater, which has eventually caused groundwater overdraft. Salt water intrusion and subsidence has occurred due to groundwater overexploitation. High concentrations of heavy metals were observed in wells around a landfill. Climate projections showed a decrease in rainfall of up to 140 mm and an increase in temperature of up to 8 °C. Groundwater storage is projected to decrease after the mid-century due to climate change. Sea level rise will continue until the end of the century. As the water and environmental challenges of Lagos are broad and the changing characteristics of the climate are expected to intensify these as projected, tackling these challenges requires a holistic approach from an integrated water resources management perspective.

Key words | climate change, distribution pipeline, general circulation model, integrated water resources management, Lagos, water pollution

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INTRODUCTION

Climate change is one of the critical issues affecting several sectors in many nations of the world. The already manifesting impacts of climate change include changes in rainfall patterns (Sa'adi *et al.* 2017; Pour *et al.* 2018; Qutbudin *et al.* 2019) and increase in temperatures (Salman *et al.* 2018; Khan *et al.* 2019) and thus, changes in the frequency and severity of extreme events like floods, droughts, heatwaves, and damages to ecosystems (Ahmed *et al.* 2015; Shahid *et al.* 2017; Pour *et al.* 2019). This will subsequently impact several sectors such as: water resources, agriculture, health, and the economy (Aich *et al.* 2016; Shiru *et al.* 2018). Water resources, which are pivotal to the development of other sectors, would be most affected by the impacts of the changing climate (Collins *et al.* 2013).

Developing countries will be more affected by the impacts of climate change due to their vulnerability and less adaptive capabilities. Therefore, the climate change risks will be much higher in developing countries with higher population densities and growth rates. These impacts may be felt more in urban areas of the developing countries where the pressure on social, economic and environmental sustainability is much higher (Pickett *et al.* 2001; Shahid *et al.* 2016). Projections show that the urban population may grow from three to five billion between 2000 and 2025 with almost all the population growth in the developing countries, particularly in Africa and Asia (United Nations Department of Economic and Social Affairs, Population Division 2016). This will put a large population in the developing cities of Asia and Africa under severe risk of climate change due to the higher population growth and lower coping capabilities in these areas.

The city of Lagos in Nigeria is currently the most populous city in Africa, and one of the fastest growing mega cities in the world. The population of Lagos has grown from 1.9 million in 1975 (United Nations Department of Economic and Social Affairs, Population Division 2016) to 22.5 million in 2016 with a growth rate of 3.2% per annum according to the Lagos Ministry of Physical Planning and Urban Development (LMPPUD 2016). The city of Lagos taps its water from both surface and ground water resources within the state. Even though Lagos seems to have sufficient water resources in terms of quantity, considering the amount of rainfall it receives, the several rivers that pass through it and the multi-layer aquifers underlying it, a lot of Lagosians are still without potable water. The main reason for water scarcity is the high population growth rate due to migration to the city from all parts of the country. Being a port city and the main commercial hub of Nigeria, Lagos attracts hundreds of thousands of people each year to work in industries. This influx of people into the city has caused over-abstraction of water resources and indiscriminate sinking of boreholes or water wells in many parts of the state not covered by the public water supply network. The generation of all sorts of solid wastes and the improper disposal and management of these wastes has caused water pollution which has further compounded the scarcity of potable water.

Lagos will experience a rapid change in environment if the current migration trend and Nigeria's population growth rates continue. The declining water tables (Longe 2011) and extensive pollution of surface and groundwater resources in many parts of the state (Olufemi *et al.* 2010) would cause a great threat to potable water availability and water resource sustainability. This may be aggravated by the changing patterns of rainfall and increasing temperature (Shiru *et al.* 2019b).

The challenges facing the water resources of Lagos, from availability and anthropogenic impacts to the efforts towards attaining sustainable management by the government and other stakeholders, are assessed in this study. Primary information was gathered through field assessments, discussions with individuals, and sample collection to investigate contamination around a landfill in the city. Changes in future rainfall and temperature compared to the past were assessed using Global Precipitation Climatology Center (GPCC) and Climate Research Unit (CRU) gridded rainfall and temperature data respectively and selected general circulation model (GCM) projections. The biases in selected GCM simulations were corrected for the projection of the climate at city scale. Gravity Recovery and Climate Experiment (GRACE) terrestrial water storage (TWS) data was used for the assessment of the possible future changes in groundwater storage.

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Finally, some of the structural and non-structural measures for adaptation and mitigation of future water challenges of the city are discussed.

STUDY AREA, DATASETS AND METHODOLOGY

Study area

The mega city of Lagos (Figure 1) lies on the Atlantic coast in the south west of Nigeria (latitude: 6° 23′ – 6°41′N; longitude 2°42′ – 3°42′E). It is a cosmopolitan city with a total area of 3,577.28 km^2, of which 22% is wetland, and 20 districts cover the rest of the area. The population of Lagos is estimated to be 22,500,000. The environment of Lagos is characterized by coastal wetlands, sandy barrier islands, beaches, low-lying tidal flats and estuaries. The average temperature of the city is 27 °C. The city receives an annual rainfall of over 2,000 mm which is the major source of groundwater recharge (Longe 2011). The geology of Lagos is made up of coastal plain sands (CPS) and recent sediments. The recent sediments form a water table aquifer which is exploited by hand-dug wells and shallow boreholes, while the CPS aquifer is a multi-layer aquifer system consisting of three aquifer horizons separated by silty or clayey layers. The latter is the main aquifer in Lagos metropolis which is generally exploited through boreholes for domestic, municipal and industrial purposes.

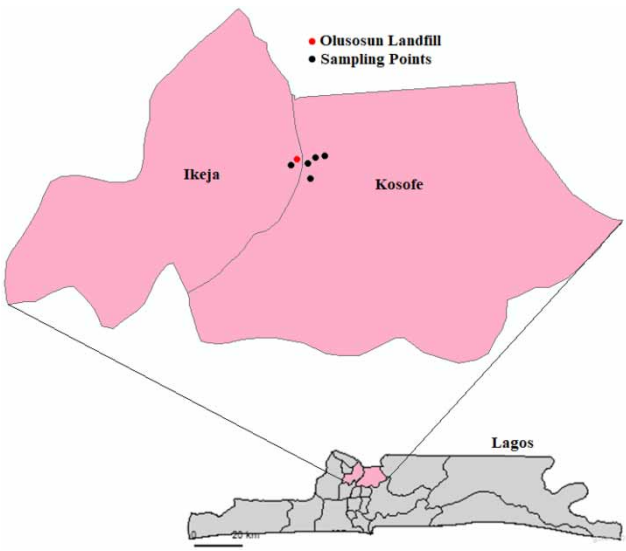

Figure 1 | Maps showing Olusosun landfill and water sample collection points and the districts of Lagos.

Lagos is Nigeria's main commercial hub as it harbors numerous industries of different scales. The port of Lagos has global and regional importance as some of the goods entering neighboring countries, such as Niger and Chad, which are landlocked, go through it.

Datasets

Historical rainfall and temperature data

Obtaining climatic data for reliable climate research is a difficult task in Nigeria as gauges are sparsely distributed and data are characterized by missing periods (Shiru *et al.* 2019a). In such situations, carefully selected gridded climate data can be used. Over some decades, several gridded climate data have emerged due to the need for longer term dense climate data. The gridded climate data developed from the observed data is considered more reliable as several analysis and quality controls are conducted on the data during their generation.

In this present study, the GPCC monthly full reanalysis data product of the Deutscher Wetterdienst and the monthly average of daily gridded temperature data CRU TS v. 3.23 of CRU, both at 0.5° spatial resolution, during the period 1961–2005 were used as the reference data. The GPCC rainfall data has the advantages of: (1) being of good quality for hydrological investigations; (2) long-term availability for wider and different ranges of study periods; (3) being a climate model derived set of data developed from the highest number of collected precipitation records; (4) time series completeness after January 1951 (Shiru *et al.* 2019a). For the CRU, all the collected data are passed through two-stage extensive manual and semi-automatic quality control measures during development. Previous studies have found both the GPCC and the CRU data suitable for climatic studies in Africa (Shiru *et al.* 2018, 2019b).

CMIP5 datasets

The Coupled Model Intercomparison Project phase 5 (CMIP5), a set of globally coordinated GCM simulations comprising historical and future climate simulations assembled

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from different modeling groups, were used in this study. In comparison to CMIP3, CMIP5 has significant improvements. A total of 20 monthly simulations of GCMs were selected for this study based on the availability of all representative concentration pathway (RCP) scenarios, namely, RCP 2.6, 4.5, 6.0, and 8.5 for Nigeria. The selected GCMs' names, their modeling centers and spatial resolutions are given in Table 1.

Methodology

The procedures used in the study for the assessment of environmental challenges of Lagos are given as follows.

i. Visual observation was conducted in several parts of Lagos to assess and analyse the environmental conditions at the various locations.
ii. Random selection of individuals for questioning about the changes that occurred in the environment over time. Information was collected through face-to-face discussions with local people from different locations. This allowed us to understand the responder's emotion, expression and discomfort in answering questions and thus helped to assess the reliability of the information provided. In the present study, the questions were repeated or the responses were verified from different respondents if any respondent was found to be doubtful.
iii. Collection and analysis of groundwater samples from different locations (Figure 1) for the asssessement of heavy metals and physicochemical properties in groundwater around the Olusosun landfill.

The procedure used for the downscaling and projection of the climate for the city is given as follows.

i. Validation of gridded GPCC rainfall and CRU temperature data using historical Global Historical Climate Network (GHCN) rainfall and temperature data by applying statistical metrics, namely percentage of bias

Table 1 | Basic information on the general circulation models used in this study for the projection of climate

No	Institution	Model name	Resolution (°, lon × lat)
1	Beijing Climate Center, China Meteorological Administration	BCC-CSM1-1	2.8 × 2.8
2		BCC-CSM1.1(m)	1.125 × 1.125
3	National Center for Atmospheric Research, USA	CCSM4	1.25 × 0.95
4		CESM1-CAM5	1.25 × 0.95
5	Commonwealth Scientific and Industrial Research Organization, Australia	CSIRO-Mk3-6-0	1.875 × 1.875
6	The First Institute of Oceanography, SOA, China	FIO-ESM	2.8 × 2.8
7	Geophysical Fluid Dynamics Laboratory, USA	GFDL-CM3	2.5 × 2.0
8		GFDL-ESM2G	2.5 × 2.0
9		GFDL-ESM2M	2.5 × 2.0
10	NASA Goddard Institute for Space Studies	GISS-E2-H	2.5 × 2.0
11		GISS-E2-R	2.5 × 2.0
12	Met Office Hadley Centre, UK	HadGEM2-AO	1.875 × 1.25
13	Met Office Hadley Centre, UK	HadGEM2-ES	1.875 × 1.25
14	Institut Pierre-Simon Laplace, France	IPSL-CM5A-LR	3.75 × 1.875
15		IPSL-CM5A-MR	2.5 × 1.25
16	The University of Tokyo, National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology	MIROC5	1.4 × 1.4
17		MIROC-ESM	2.8 × 2.8
18		MIROC-ESM-CHEM	2.8 × 2.8
19	Meteorological Research Institute, Japan	MRI-CGCM3	1.25 × 1.25
20	Norwegian Meteorological Institute, Norway	NorESM1-M	2.5 × 1.875

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(Pbias), normalized root mean square error (NRMSE%), Nash–Sutcliff efficiency (NSE), modified index of agreement (md), and volumetric efficiency (VE).

ii. Rainfall and temperature data of GCM historical run were re-gridded to $2^\circ \times 2^\circ$ resolution. The GPCC and CRU data were also aggregated to $2^\circ \times 2^\circ$ resolution to comply with GCM data.

iii. Entropy-based methods were used to assess the similarity of GCM rainfall/temperature with GPCC/CRU rainfall/temperature for the period 1961–2005 and the best GCMs in terms of their ability to simulate GPCC/CRU rainfall/temperature were selected.

iv. Selected GCMs were bias corrected at grid level using the gridded GPCC rainfall and CRU temperature as reference data.

v. Time series of the future projections of rainfall and temperature for all RCPs were subtracted from the mean GPCC rainfall and CRU temperature for the base period (1971–2000) to assess the future changes in climate of the city.

The GCMs were selected using entropy based methods and a multi-criteria decision-making (MCDM) system. Information aggregation from various sources using MCDM can be a vital tool for ranking GCMs from many alternatives (Shiru *et al.* 2019a). In this study we employed an MCDM based approach in which weights generated for different GCMs using entropy gain (EG), gain ratio (GR), and symmetrical uncertainty (SU) methods were used for their ranking. In the proposed approach, the number of grid points where a model achieves a particular rank from the total number of grid points was obtained from a payoff matrix. As this study uses 20 GCMs which were ranked between 1 and 20, the payoff matrix was 20×20. The matrix was used for the final ranking of the GCMs based on the frequency of ranks obtained at different grid points. A GCM that obtained higher weights due to higher frequencies of occurrence was given a higher ranking.

The procedure used for the assessessment of the impacts of climate change on groundwater storage is given as follows:

i. The GPCC rainfall and CRU temperature for the months for which GRACE data are available (January 2002 – December 2016) were prepared.

ii. Support vector machine (SVM) and random forest (RF) models were developed using GPCC rainfall and CRU temperature as input and GRACE groundwater storage anomaly as output.

iii. Different performance indices were used to assess the performance of the SVM and RF models and the best model was selected for simulation of groundwater from rainfall and temperature.

iv. Time series of the future changes in groundwater storage for all RCPs were generated from the projected rainfall and temperature using the selected model.

STUDY OUTCOMES AND RESULTS

Challenges of water resources and anthropogenic impacts

Water resource availability

The availability of fresh surface and groundwater resources in Lagos, including the issues relating to pipeline distribution and network coverage, are discussed in this section.

After the commissioning of the first water works in Lagos in 1910, the Iju water works with a capacity of 11,000 m^3/day, a series of expansions, building of new mega and mini water works, and various developmental programs of the Lagos Water Corporation (LWC) have not been able to solve the city's water problems. With a design capacity of 2.4 million gallons per day (MGD), the Iju treatment plant has seen several schemes for expansion including the installing of new treatment plants and other water equipment in order to meet the increasing water demand due to the increasing population of Lagos (LSG 2013). The Ishasi and Adiyan water works were constructed in the years 1976 and 1991 respectively in order to mitigate the water supply problem. The amount of total water supply from the water works is currently 210 MGD. However, supply still remains lower than the current demand for water in the city.

While water availability is the major problem in some parts of the world, especially in semi-arid and arid regions, this is mostly not the case in Nigeria. The country has adequate surface and ground water resources that can meet its

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demands for potable water. However, spatial and temporal distribution of water has led to scarcity in some locations, especially in the northern part of the country. Lagos boasts a vast amount of both surface and ground water resources. This is due to the flow of several rivers, including Yewa, Ogun, and Ilo, through the city from which Lagos taps most of its water resources. Also, the high amount of rainfall (>2,000 mm/year) received by the city helps recharge the aquifers and allows for a good amount of groundwater reserve. About 10 MGD groundwater is abstracted from the multi-layer aquifers to meet the water demands of the city. Abstracting such large amounts of groundwater has caused over drawing of the aquifers and a gradual decline of the water table (Longe *et al.* 1987).

The coverage of public water distribution pipelines from the LWC is limited. The public water supply of Lagos covers only about 35% of the metropolitan population with the remainder (65%) relying on private wells, boreholes and water vendors. This caused the indiscriminate installation of boreholes and hand dug wells and resulted in significant impacts on groundwater tables. Also, about 60% of the distributed water from the corporation is lost due to pipeline leakage, illegal connections, and excess water usage due to flat rate water tariffs (World Bank 2000).

The LWC, in a bid to surmount the water shortage problems and ensure improved supply to the increasing population, developed a Water Supply Master plan as a 'Road Map' to achieve a water production capacity of 745 MGD for Lagos by the year 2020. It is important to mention that the water demand of the city transcends water availability. The water challenges due to quality are more than the challenges due to quantity for the city. The anthropogenic impacts on the water quality of Lagos are discussed in the following section.

Anthropogenic impacts

Fresh water quality remains one of the most critical environmental and sustainability issues of the 21st century. Due to several reasons the water quality of Lagos has continually deteriorated over many years. This is stimulated by the continuous influx of people from different parts of the country and the world, attracted to the many opportunities it provides. Due to this, as many as 200 slums have sprung up in different parts of Lagos and these are among the major contributors to pollution. Figure 2 shows a typical slum in an area of Lagos. Aside from parts of Abuja, the Nigerian capital, and a few areas of Lagos, central sewerage systems are lacking in Nigeria and sewage is either left lying stagnant or are disposed through storm water drainage systems. The common types of convenience in the slums are either open defecation or pit latrines. These latrines, which are usually not lined, are a common source of diffuse pollution as they are often dug in high water table areas and thus pollute the groundwater resources from which the residents get water. This has given rise to outbreaks of waterborne diseases such as the outbreak which occurred in Lagos in 2010 (LSG 2013). In addition, sewage of various types is disposed of into trenches (Figure 3) which eventually find their way into lagoons or other water bodies. This not only poses a threat to the surrounding communities, but to the aquatic life in surface waters.

Figure 2 | A typical slum in Lagos, the most populated city of Nigeria (*source*: Oluwatoyin Bayagbon).

Figure 3 | Sewage disposal in a trench in Lagos (*source*: Olatubosun Obayomi).

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Industrialization is another major cause of pollution of water resources in Lagos. Lagos has numerous small, medium and large scale industries including chemical, pharmaceuticals, personal care products, breweries, metals, food and plastics. Some of the companies dispose of their effluents directly into the environment with little or no treatment. For instance, the Lagos State Environmental Protection Agency (LASEPA 2013) reported the activities of a galvanizing and a metal company that discharge their wastes (oil and sludge) directly into streams and rivers. The companies were reported to have been closed down by the agency. Effluents disposed of directly onto the surface of the ground are also likely to reach the groundwater table over time, contaminating the resource, if the contaminants present are not attenuated.

The city of Lagos generates several tons of solid waste annually, originating from industrial and domestic disposal. The management of these wastes, from collection to final disposal, has been a great challenge. Typically, waste sorting is not practiced in Nigeria making waste management a problem. Most waste generated in Lagos ends up in landfill. However, most of the landfills in Lagos are old and are lacking improved leachates collection processes and leachates monitoring as practiced in developed countries. Also, some of the landfills need to be decommissioned as they have built up excessive methane which constitutes a serious threat to the inhabitants of the areas. For example, there was a fire incident at Olusosun landfill in the Ojota area of Lagos in 2018. Leachate percolating down the subsurface also poses a great risk to the ground water resource around landfills. Figure 4 shows a depression filled with solid wastes including machinery and water accumulation from rainfall at the Olusosun municipal landfill.

Figure 4 | Olusosun landfill in the Ojota area of Lagos (*source*: M.S. Shiru).

Heavy metal concentration and some physicochemical properties in groundwater obtained through the analysis of groundwater samples collected around the Olusosun landfill area at Ojota are presented in Tables 2 and 3 respectively. The results revealed that heavy metals such as cadmium, chromium, lead, and nickel exceeded the guidelines (Table 4) of the World Health Organization (WHO). The concentrations of lead were highest at the locations Ojota Motor Park and Adesina Street, closest to the landfill. However, the highest concentration of nickel was observed at the location furthest from the landfill, Ogudu road. This suggests that there may be other sources of pollution in the area. All the water samples were found to be acidic except for the sample from Adesina Street. The electrical conductivities of the samples were also high except for the samples from Ojota Motor Park. The temperatures of the samples were lower than 30 °C for all the cases when they were collected.

The sight of piles of rubbish in different areas of Lagos has become very common in recent years (Vanguard 2018). Figure 5(a) shows a heap of rubbish along a road in Lagos while Figure 5(b) shows rubbish by the roadside and in drainage at the Apapa area of Lagos. The management of wastes

Table 2 | Concentrations (mg/L) of heavy metals in groundwater samples collected from five locations

Sampling Location	Sample I.D.	Cu	Fe	Cd	Cr	Pb	Zn	Ni
OJota motor park	1	1.000	0.111	0.100	0.300	0.087	0.083	0.308
Ogudu Road	2	0.545	0.148	0.200	0.400	0.043	0.083	0.769
Adesina street	3	0.273	0.074	0.200	0.200	0.087	0.167	0.615
Fadayomi street 1	4	0.455	0.111	0.100	0.600	0.043	0.056	0.692
Fadayomi street 2	5	0.182	0.074	0.200	0.200	0.043	0.083	0.538

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Table 3 | Physicochemical properties of groundwater samples collected from five locations

Sampling location	Sample I.D.	pH	EC (μS/cm)	Temp. °C
Ojota motor park	1	6.2	24.3	27.3
Ogudu Road	2	5.4	289.0	27.1
Adesina street	3	7.4	319.0	27.0
Fadayomi street 1	4	6.6	341.0	27.0
Fadayomi street 2	5	6.6	485.0	26.9

in Lagos has worsened in recent years. For example, about 300 supervisors of street sweepers were recently sacked by the state government. The exact cause of this is not known, but is probably attributable to poor performance (Vanguard 2018). The littering of the streets or public places by rubbish has serious implications for the city. This could lead to the breeding of rodents/vectors which carry various diseases. The foul smells from the rubbish heap and the sight of it can also be very unpleasant to residents.

Other anthropogenic consequences are the over-abstraction of ground water resources which has led to land subsidence in some areas. For example, some buildings have been abandoned or demolished for redevelopment due to land subsidence in the Idumota area of Lagos Island. Figure 6 shows two tilted buildings which have been abandoned as a result of subsidence. Verbal discussions with some residents revealed that there are different opinions as to the causes of subsidence in the Idumota area. While some are of the opinion that the occurrence of subsidence can be attributed to over-abstraction of groundwater, others feel subsidence is occurring due to the reclamation of some areas from the Atlantic Ocean. This makes the causes of subsidence in the area a subject of further research. Extensive salt water intrusion has been reported in some areas including the Adeniji Adele, Victoria Island, and the CMS areas of Lagos. As reported by Olufemi *et al.* (2010), water samples collected from Adeniji Adele (1,251.2 μs/cm), CMS (1,520.0 μs/cm) and Victoria Island (1,565.2 μs/cm) exceeded the permissible values of WHO.

Climate change and groundwater storage projection of Lagos

Historical data validation

Using the GHCN as the observed data for Nigeria, the GPCC rainfall and the CRU average temperature for Nigeria

Table 4 | Heavy metal concentration guidelines (WHO 2006)

Metal	Cu	Fe	Cd	Cr	Pb	Zn	Ni
Guideline value (mg/L)	2.00	1–3	0.003	0.05	0.01	Not required	0.07

Figure 5 | (a) Heap of rubbish by a roadside and in drainage in Lagos (*source*: Vanguard 2018). (b) Rubbish by the roadside in the Apapa area of Lagos (*source*: Vanguard 2018).

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Figure 6 | Abandoned tilted buildings due to land subsidence at the Idumota area of Lagos (*source*: M. S. Shiru).

were validated using NRMSE, NSE, MD, Pbias, and VE. The performances of GPCC rainfall and CRU average temperature at selected stations are given in Figure 7. It can be seen from the metrics that the GPCC rainfall data and the CRU average temperature data were able to replicate the observed rainfall and observed temperature characteristics of Nigeria.

Projected changes in rainfall

The anomalies between the rainfalls (2010–2099) projected by the selected GCMs and the mean of the historical GPCC rainfall (1971–2000) in Lagos showed that rainfall will decrease under all RCPs in the future (Figure 8). The decreases in rainfall are projected to be the highest by HadGEM2-ES GCM, up to 140 mm under RCP 2.6, while increases in rainfall are projected for a few years at the end of the century by the GCMs; CESM1_CAM5, CSIRO_Mk3-6-0, and HadGEM2-ES.

Projected changes in temperature

The anomalies between the average temperatures (2010–2099) projected by the selected GCMs from the mean of the historical CRU temperature (1971–2000) in Lagos for different RCPs are shown in Figure 9. Figure 9

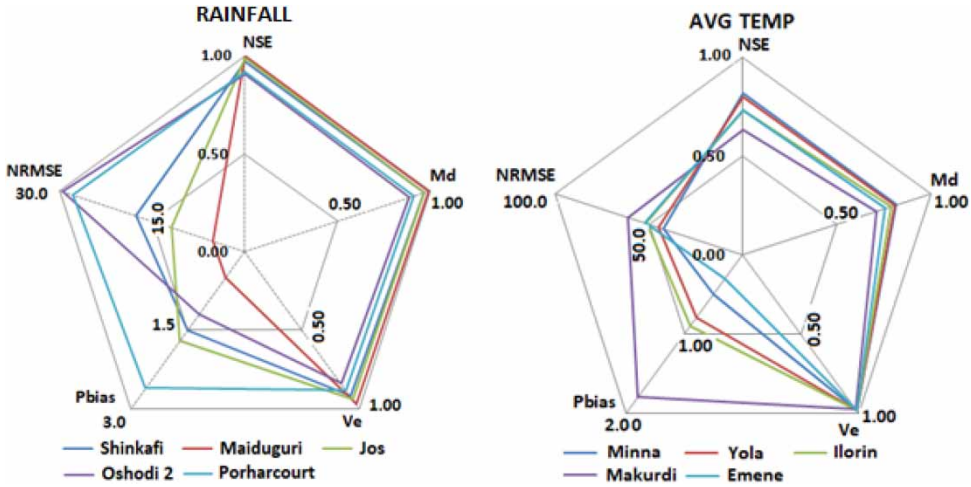

Figure 7 | The performances of GPCC rainfall and CRU average temperature at four locations of Nigeria based on different statistical metrics.

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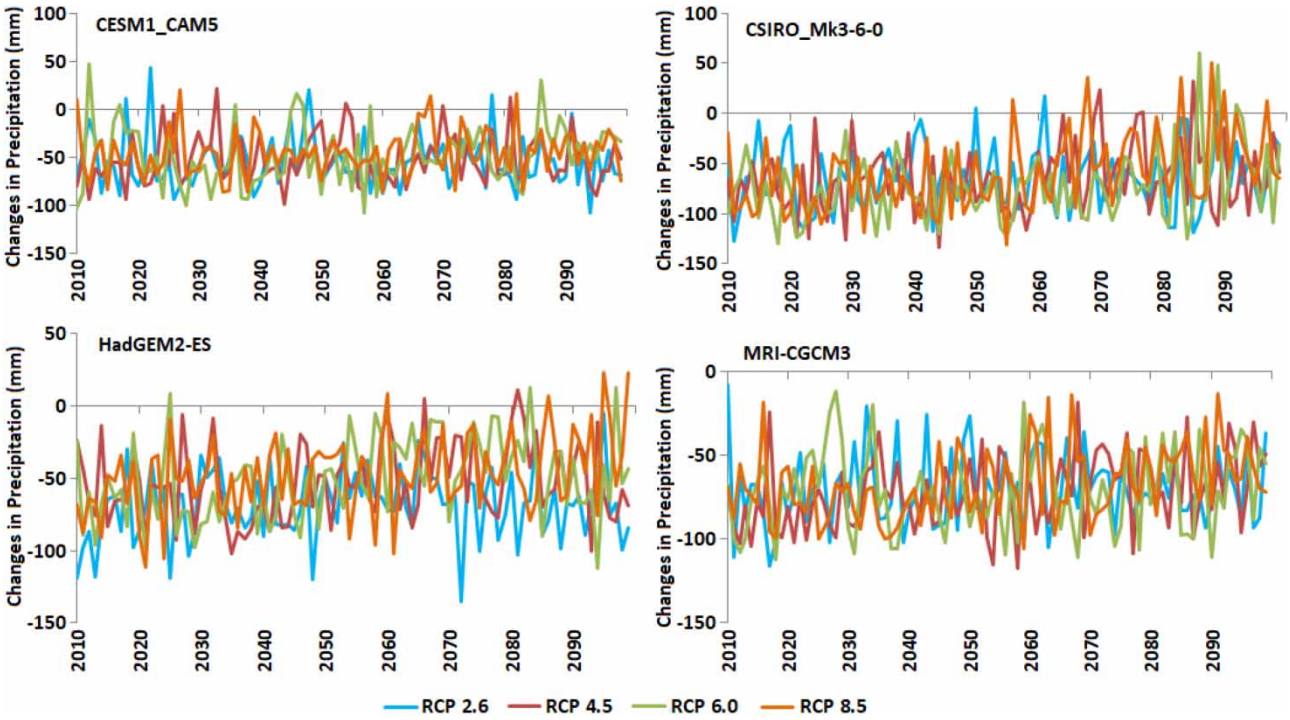

Figure 8 | The annual rainfall anomaly in Lagos projected for four RCPs.

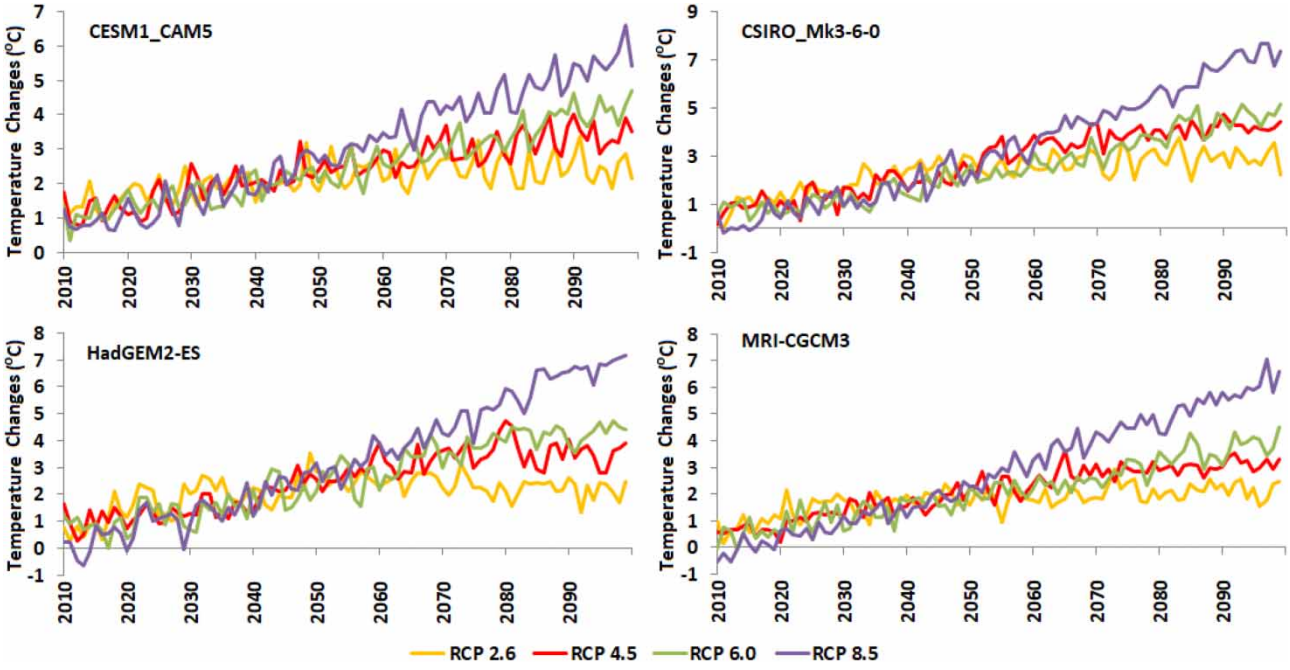

Figure 9 | Average daily temperature anomaly in Lagos projected for four RCPs.

shows that the temperature will increase continuously over time until the end of the present century. Temperature changes are projected to be highest under RCP 8.5 at the end of the century (8 °C rise). The least changes in temperature are projected for RCP 2.6 at the end of the century.

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Projected changes in groundwater storage

Changes in groundwater storage for the city of Lagos are presented in Figure 10. Figure 10 shows the CESM1_CAM5 projected decline of storage after the mid-century with the highest decline for RCP 8.5. The CSIRO_Mk3-6-0 GCM showed a continuous decline in groundwater storage with the highest decline at the end of the century. The HadGEM2-ES and MRI-CGCM3 also showed decreases in groundwater storage at the end of the century with the highest decrease for RCP 8.5.

Sea level rise

Figure 11 shows the changes in sea level between 1980 and 2100. It also shows that the sea-level rise in Lagos will be continuous and could rise up to 1 m by 2100.

SUSTAINABLE WATER RESOURCE AND ENVIRONMENTAL MANAGEMENT

Water supply and quality have been impacted by increasing population, urbanization, industrialization, and climate change in Lagos city. Attaining sustainable water resource and environmental management remains a challenge in the city and across the globe. However, efficient and holistic water management and infrastructural development integrating sustainable watershed scale strategies such as the 'Sustainable Water Management Improves Tomorrows Cities Health' of the European Union are evolving, which aim to bring a shift in urban water management away from the existing and ad hoc solutions to urban water management towards a more integrated approach. This, with other strategies, could be adopted by Lagos to solve the water and environmental issues. However, it is imperative

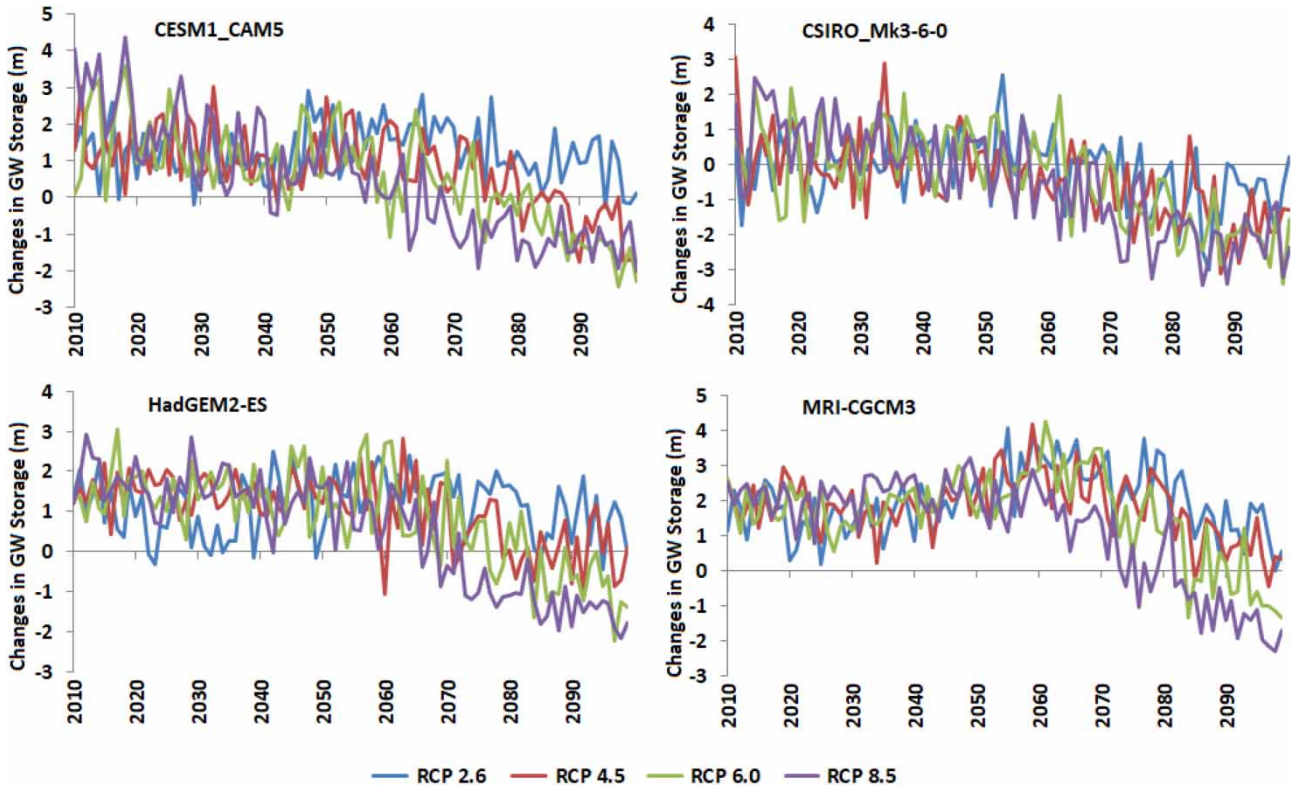

Figure 10 | Changes in groundwater storage for all RCPs within a location in Lagos.

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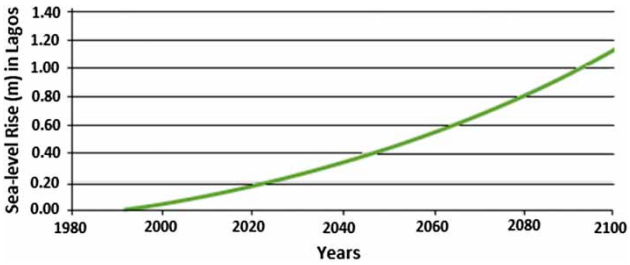

Figure 11 | Changes in sea level along the coast of Lagos (*source*: UNIDO).

to consider local factors such as the laws governing water use and abstraction, land use, environmental laws and tailoring such approaches to fit a local area.

Efforts have been made by the past and present governments with investments in several water projects in the state. However, the efforts are unnoticeable due to several decades of negligence, over-population, non-abiding of laws, and improper review of existing laws. The solving of the water and environmental issues in Lagos requires a holistic approach with collaboration between the environmental and water sectors through an integrated water resources management (IWRM) approach with involvement of all stakeholders. Some of the efforts made by the Lagos State Government (LSG) and other stakeholders to solve the water and environmental issues within the state are discussed in the following sections. Besides, suggestions are given for mitigating the current and projected impacts of the changing climate on the water resources of the state.

Structural measures

Improved infrastructures

Ideally, the responsibility for provision of infrastructures should not rest on the government alone. In advanced countries the water and other infrastructural services, such as provision of electricity, are provided through private or a public–private partnership approach. However, the responsibility for the provision of basic infrastructures in Nigeria has been on the government for several decades. This has resulted in improper management due to the 'indifferent attitudes' of most staff of different agencies, departments and ministries. In Nigeria, privately owned companies or joint ventures between private companies and government are known to be better managed as they are profit-oriented. This is the case in the communication sector in which improvement was achieved after the involvement of private companies which saw competition among them.

Electricity is important for the pumping and distribution of water. The supply of electricity in many areas of Nigeria is irregular. This has increased the cost of production and distribution of water resources as the process is often carried out by generators. This can also have implications for the time needed for water supply to be implemented. The water distribution pipes in Lagos are mostly old and often damaged due to vandalism. There is a need for replacement of these old pipes and networking to other areas. As the financial implications may be high for the government, the private investors can be involved in water supply. However, it is important that the government regulates prices to prevent the public being exploited.

Non-structural measures

Review of water and environmental laws

The laws existing for the abstraction of water resources and prevention and control of water pollution in Nigeria are sometimes inadequate or duplicated. There is no specificity in the existing laws as to where the final control of water resources lies between the several water agencies and departments, especially those between the states and the federal government. The legal provisions for water management give similar authority to different institutions without clear rules in the division of responsibilities and conflict management (Ijaiya 2013). In terms of water allocation, there are no provisions for allocating the resource to different users for different purposes. This has the consequence of undesired overuse of water resources in some areas.

In 2012, the LSG recognized the need for a review of the Lagos water sector laws with consideration of new challenges facing the sector including climate change, population explosion, and duplication of the roles of ministries, departments and agencies (LSG 2013). The law of water abstraction in Nigeria permits the owner of a piece of land or property to abstract groundwater resources freely as much as they desire. Such laws encourage wastage of water resources since little or nothing is paid, especially for the

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private borehole or well owners. There should be allocation of the amount of water abstracted by individual households/industries with charges on the extra abstractions as practiced in some developed countries. This will help prevent the water tables from declining rapidly as people will be more prudent in using the water resources. Furthermore, cases of subsidence can be reduced and there could be a reduction in salt water intrusion due to rising groundwater tables. As the laws governing effluent disposal are not always obeyed by many industries, the 'polluter pays' law should be implemented and industries should be forced to clean up whichever environment they pollute. This will serve as a deterrent to other companies and most would prefer efficient treatment of effluents and appropriate disposal of them instead of paying heavy fines for polluting the environment.

While it is important to separate the roles of the ministries, departments and agencies of the LSG, it is essential for them to collaborate, especially where their functions overlap to reach the goals of achieving a sustainable water resource and environmental management. A synergy between them, even when tasked with different duties, will be beneficial for the city. For example, while the role of the ministry of water resources is water provision and management, the ministry or agencies of the environment can assist in protecting the environment, thereby preventing the contamination of the water resource.

Improved waste management

Due to industrialization and the high population, the amount of waste generated in Lagos state is much higher compared to other states in Nigeria. Improper waste management constitutes one of the main methods by which water resources are polluted. Unlike in the developed world where waste management methods have improved, they are still not advanced in Lagos. The problem of waste management originates from homes in Lagos, as there is no sorting of waste as practiced in many countries. Waste sorting has been found to increase the generation of recyclable waste. It has been revealed that high water contents and high percentages of food waste contribute to the high cost and low efficiency in the disposal of waste.

Organic wastes which are sources of energy end up at landfills in Lagos as opposed to energy generation facilities in advanced countries. These wastes are the main sources of pollution as they decay over time and leach through the unsaturated zones, contaminating ground waters. As most of the landfills in Lagos are old, new technologies for collecting and monitoring leachates are lacking and thus, the groundwater in such areas becomes susceptible to contamination. It is therefore important to decommission some of the old landfills and commission new ones with more advanced management technologies.

In a bid to combat the problem of sewage management, the LSG established the Lagos State waste water management office in 2010. There are now four Lagos state-owned waste water treatment plants located in Abesan, Satellite town, Amuwo Odofin, and Alausa Secretariat in addition to three federal government-owned, and several privately owned mini plants (LSG 2013). This, according to the LSG (2013), only caters for about 0.04% of the Lagos population.

Waste disposal is often not paid for by the general public in Lagos, and in Nigeria at large. It is believed that it is the responsibility of the government to do so. Hence, waste is disposed of in dustbins or other containers provided by the government. However, where such facilities are lacking or inadequate, people dispose of their refuse at any available location, usually open spaces, without considering the health or environmental implications. Some of this waste is disposed of in storm water drainages/channels and can block drains or reduce their capacities, thereby worsening floods which are a common event in Lagos during the rainy season.

The education of the general public on the health and environmental implications of these acts and of the need to be willing to pay for disposing of their waste are required to solve these problems. It is also important that waste disposal facilities are made available at strategic locations and should be emptied in time so that overflowing or littering can be avoided. The monthly environmental activity which has been canceled by the present LSG (Vanguard 2018) should be restored as it will help mitigate the menace of littering across the state. There is the need for more involvement of private investors in the management of waste in the state since such projects can be capital intensive. For example, industries which cannot treat their waste water can employ the services of a waste water management

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company to do this. There is also a need for the government to implement a general sewage system for districts as this will help reduce the rate of pollution of water resources.

Land use review

The growth and physical expansion rate in urban areas around the world has changed rapidly in recent times, especially in the developing world (Abiodun *et al.* 2011). This has not only led to competition for space and conflicting use of lands, but has also impacted natural habitats and natural resources. For water resources, improper land use decisions can result in changes in the natural watershed and can compromise the quality of water resources. The different land use purposes are not always clearly defined, not only in Lagos but across Nigeria. Due to the continuous increase in population and demand for space, residential areas have developed to meet and even interlock with areas that were originally planned for industrial purposes. It is not uncommon to see industries of various types sited in residential areas in Lagos. Some of these industries dispose of their waste directly into the environment, thereby contaminating wells in residential areas. This can have a significant impact on the air and water quality of residential areas.

To solve this issue, the appropriate planning of new areas for different purposes should not be ignored. In already mixed industrial and residential areas, extensive investigations of the water resources and environment should be conducted to ascertain the possible impacts of the industries on the area. If the impacts are significant and can cause devastating damage, the industry should be relocated, otherwise continuous monitoring of the environment should be carried out at specified intervals.

Integrated water resources management

IWRM is a process which involves the coordinated development and management of water, land, and related resources for maximum economic and social benefits in a fair manner to achieve sustainability in ecosystems and the environment. IWRM has become increasingly important due to the limitations of the fresh water resources which are becoming increasingly polluted due to the population explosion, especially in urban areas in many parts of the world. IWRM considers water resources from a number of perspectives, helping to make the appropriate decisions in water use and management. IWRM has to take into account the following: (i) the water resources, considering the entire hydrological cycle; (ii) the water users, all sectors that use water, and the stakeholders; (iii) the water resources' spatial distribution and uses, and the various spatial scales at which there is water management from individual users, user groups, watershed, catchment, and the existing institutional arrangements existing at the various scales; and (iv) the temporal scale, considering the temporal variation in water resources availability and demand.

The adoption of IWRM is the most effective approach through which the city of Lagos can achieve sustainable water resources management. The LSG has enacted some policies towards achieving its vision of sustainable water resources management. According to these policies, it shall ensure that the management of water services minimizes any adverse environmental impacts and protects water resources from degradation by effluents from industrial and agricultural works. With this development, it is anticipated that the set goals will be achieved.

Adaptation planning and mitigation measures against climate change

Considering the 2 °C limit, Article 2(2) of the COP21 Paris Agreement acknowledges that even though there is a general responsibility for mitigating climate change impacts, there is the need for differentiation of the different parties involved in the achievement of the mitigation. The Agreement emphasizes that there shall be by each party, preparation, communication, and maintenance of successive nationally determined contributions to achieve, and parties shall pursue domestic mitigation measures aimed at achieving the objectives of such contributions. Article 2(4) of the agreement states the need to distinguish the expected actions from the developed country parties and the developing country parties.

Compared to the developed worlds, developing countries lack the full capabilities for dealing with climate change (Collins *et al.* 2013). These areas are known to have the highest populations, also making them more vulnerable to the various impacts of the changing climate. Cities in

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areas such as Lagos are also experiencing the highest population growth. There is a variation in adaptation responses to climate change from city to city across the globe. There is also variation in the period of response, if it has to be immediate, i.e. short-term, or over a longer period, i.e. long-term.

For the city of Lagos, while there are policies governing water and environmental management, the policies streamlined to combating climate change are not known. The known water resources and environmental laws and policies are also not strictly implemented which is why Lagos is faced with many water resources and environmental challenges. While projections for changes in groundwater storage show that storage is going to increase in the early part of the century for the models CESM1_CAM5, HadGEM2-ES and MRI-CGCM3, all models show that after the mid-century, groundwater storage is going to decrease. Groundwater, which is seen as a buffer to increased water demand during droughts or water scarcity, may face intense over-abstraction in Lagos due to its projected population increase of 85 to 100 million by the end of the century. It is therefore crucial to consider short-term plans for the projected increase in temperature, decrease in rainfall, and increase in sea level.

To develop and achieve some of the policies for combating the climate change menace of Lagos, the following approaches can be implemented:

i. Identify extensively the current contributors to increased water and environmental problems and how they affect the climate.
ii. Sensitization of the public and all stakeholders regarding the impacts of their actions/inactions on the environment and climate.
iii. Formulation of policies, e.g. short-term policies in cutting down GHGs emission from transportation and industries of Lagos.
iv. Development of adaptation and impact mitigation measures, e.g. controlled developments at the shores of the coasts, improved water resources management for the various users.
v. Implementation of the policies and continuous evaluation and monitoring of the existing policies.
vi. Adjustment of the policies against the environmental changes.

CONCLUSIONS

The population explosion of Lagos is seen to be the major cause of infrastructural decay in the city. Due to its appeal for business and other opportunities, the city attracts several thousands of people every day. This has led to the existence of many slums and various industries which contribute to massive environmental pollution within the city. Even though the government is making efforts to combat the pollution menace, keeping pace is difficult because of the negligence over several decades. In more recent times, the LSG has made tremendous efforts to combat some of the problems. However, solving the water and environmental issues of Lagos requires an integrated approach and joint efforts from governments at various levels, nongovernmental organizations, and other stakeholders.

There is a need for the decongestion or upgrading of the slums which contribute to massive environmental damage in the city. Stricter environmental laws, such as the polluter pays, can be adopted to check the rate of environmental degradation especially from industries. Water abstraction laws should be reviewed to check the rate of depletion of the aquifers, thereby reducing the rate of subsidence and salt water intrusion. For better management of water resources, water prices should be proportionately paid by individuals and industries based on abstraction and not just on flat tariff rates. This will discourage water waste in the city. As most of the public is not aware of climate change and its various impacts, it is critical to enlighten the urban population about the implications of climate change.

The projections for rainfall and temperature show rainfall to be decreasing and temperature to be increasing compared to the past. This indicates that there would be increased evaporation which may severely affect surface water, leading to over-abstraction of groundwater resources. This may intensify at the end of the century when groundwater storage is projected to decrease. Some parts of Lagos, such as Vitoria Island which is already experiencing

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coastal flooding due to the increase in sea level, may further be affected by the projected increase in sea level. Immediate short-term plans are therefore critical for coastal flood controls in such areas. Immediate, mid-, and long-term plans are crucial for water resources and environmental management of Lagos in a holistic manner, especially in the areas of environmental pollution. The development of a water resources conservation plan is also required for mitigation of climate change impacts on water resources.

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