Climate projection ensemble as support to water management and irrigation in Nigeria
M. Santini, R. Valentini and R. Cervigni

ABSTRACT

Hydrological modeling was used for projecting average annual water availability in Nigeria in the future, comparing a baseline (1976–2005) with a 30-year future (2036–2065) period, simulated under an ensemble of ten climate projections. Simulations converged in projecting by mid-century an increase in water flows for almost half of the country. Models agreed also in projecting decrease and stability in water flows for 13% of the country, while uncertainty covers about one-third of Nigeria. Lack of agreement among different climate models on precipitation and in flow makes it difficult to project how much water will be effectively available in the future for irrigation. Reservoir size is usually designed to ensure sufficient storage providing a given yield based on past climate. The objective of this paper is evaluating what storage investments are suitable for meeting irrigation development targets under as many climate outcomes as possible. A simple methodology for more robust investment planning is suggested and the risk of over- or under-designing storage based on past climate is exemplified. This preliminary study shows that, for more than half of the country, using the historical climate as a guide to the design of future storage might lead to inappropriate investment decisions, resulting in excessive or insufficient capital outlays. The conclusions of the paper do not entail endorsement by the World Bank or its Board of Directors.

Key words | climate change impacts, ensemble, robust decision-making, uncertainty, water resources

INTRODUCTION

While the future of the global climate is more or less clear, the regional climatic differentiation is still affected by uncertainty (Hawkins & Sutton 2009, 2011). The warming dynamics are globally and regionally evident, whereas precipitation patterns are indistinct, as rainfall is expected to increase in some regions and decrease in others (IPCC 2007; Schiermeier 2010). In the future, change and variability in climate variables will continue to have implications for water resource planning and management throughout the world (Buytaert et al. 2010).

Results of the study conducted by Ojo et al. (2004) on West Africa revealed high spatial and temporal variations in characteristics of rainfall and hydrological systems, both locally and regionally. In particular, as part of the West Africa region, Nigeria was strongly affected by changes in climate. Data from the Nigerian Meteorological Agency (NIMET) on the period 1941–2000 highlighted higher spatial heterogeneity for rainfall regime than for temperature (Building Nigeria’s Response to Climate Change, BNRCC 2011). In terms of impacts, while an advancing desertification trend is evident in the northern part of the country, weather-related disasters, such as flooding, and climate-related phenomena, such as sea level rise and coastal erosion, are increasing in the south (Enete & Ezenwanji 2011).

Water cycle plays the key role in the above-mentioned changes. Water resources are abundant in Nigeria; however, they are not evenly distributed across the country. In addition, water availability varies from year to year and from season to season. The majority of regions in the country frequently experience water-related problems, such as shortages (droughts), excess (floods), and water quality issues (Enete & Ezenwanji 2011).
The adverse effects of future climate change and associated environmental and socioeconomic problems may exacerbate the already critical situation in many parts of Nigeria (Aizebeokhai 2011). Indeed, also reflecting past trends, it is reasonable to predict that rainfall is likely to increase in some areas and decrease in other parts of the country, although there is no agreement among modeling studies in this regard (Odekunle & Adejuwon 2007; BNRCC 2011). In addition, the water deficit – supply minus demands – projection calculated for Nigeria is significant and is assumed will increase in the next decades, especially in urban areas (Ojo 2003).

Pessimistic climate change projections, ever-increasing population pressures – from 39.6 to 104.9 million people from 1996 to 2030 estimated in Ojo (2003) – and rising water deficit indicate the need for formulation of coherent policies and programs to optimize management and conservation of water resources and to support actions and responses to adapt to climate and social change impacts.

Considering government targets, water use for irrigation and hydro-energy production will remain one of the major drivers of Nigeria’s economic growth in the upcoming years (Master Plans, Nation’s Vision 20: 2020). To project the potential impacts in Nigeria’s resource potential to sustain the major economic sectors, integration of both climate changes and adaptations to those changes into the decision formulation is of strategic importance. It is equally important to improve awareness about the uncertainty in the spatiotemporal variation of climate.

Traditional climate change impact assessment tools are rather limited in their application, partially because only a few change scenarios were used to evaluate the response of a system at a future time (Smith et al. 2001). Due to its multifaceted nature involving different regions, sectors, and resources, impact assessment is complex in itself. However, under the concept of ensemble forecasting (e.g., Araújo & New 2007), it is possible to handle uncertainties associated with climate risk analysis by using a range of scenarios for a given impact rather than relying on a single case. Each individual alternative view of the future in an ensemble study will not necessarily reflect the most probable prospects but, as a whole, simulations suggest the range of possible changes.

Since the future rainfall and its variability in Nigeria are uncertain, also characterized with a high spatial heterogeneity, in this work climate change impacts pertaining to water resources are addressed taking into account the probability that they will occur. To achieve this objective, multiple medium-term (up to 2,065) future projections on water availability are compared with respect to a specific reference period (i.e., under no climate change conditions). Further, the ensemble of projections is evaluated on how they can support robust adaptation strategies/responses for irrigation development. Indeed, to assess whether investment decisions on water resource management are robust under a wide range of climatic outcomes – i.e., are likely to deliver irrigation under as many climate outcome as possible – hydrological modeling results are used to expand the impact analysis.

This work is part of and builds upon an agreement between The World Bank and the Federal Government of Nigeria to undertake a climate risk analysis (Cervigni et al. 2013). Among the objectives of this analysis, developing and sharing a solid knowledge platform on vulnerabilities to climate shocks for selected sectors (agriculture, water resources, and coastal zone development) and their consequences under Nigeria’s developmental targets are of central importance.

WATER RESOURCE MANAGEMENT AND IRRIGATION IN NIGERIA

With about 1,800 m³/capita/year of total renewable water resources, Nigeria is well above the threshold typically used to define water scarcity (1,000 m³/capita/year). The coverage of water supply in Nigeria ranges from 55 to 60% for urban areas, 55 to 50% for rural areas, and 30 to 52% for semi-urban areas (The National Water Supply and Sanitation Baseline 2006–2007). The shares of water withdrawal (8 km³/year) for agricultural (farming, irrigation, and livestock), domestic, and industrial consumption are 69, 21, and 10%, respectively (AQUASTAT-FAO; http://www.fao.org/nr/water/aquastat/main/index.stm).

Three main categories of irrigation development exist in Nigeria, as outlined in an ICID report (http://www.icid.org/cp_nigeria.html), namely: (1) public irrigation schemes (formal irrigation) under government control; (2) farmer owned and operated irrigation schemes (informal...
irrigation), receiving assistance from government in the form of subsidies and training; and (3) residual flood plains, where no governmental aid is supplied and the system is based on traditional irrigation practices.

As irrigated production can buffer the impacts of drought and affect rain-fed production, irrigation expansion via efficient water resource management is recognized as a key ingredient for reaching the agricultural growth targets set by the government (The World Bank 2010). In particular, the national targets for Nigeria, as reported in Vision 20: 2020 http://www.npc.gov.ng/home/doc.aspx?mCatID=68253 (VN2020 hereafter), aspire to increase irrigation to 25% of the cultivated areas (currently 1%) by 2020.

In 1995, the Japan International Cooperation Agency (JICA) produced the National Water Resources Master Plan (NWRMP) for Nigeria. This was intended to help in optimizing water use and to provide the appropriate development scenarios on a short-term (year 2000) and medium-term (year 2020) basis in meeting the predicted social and economic demand for the Nigerian regions over a wide range of potentials. According to projections outlined in the NWRMP, incremental water storage of 2 billion cubic meters per annum will be required between 2012 and 2020 to meet the required water demand in the country. Currently, JICA supports the Federal Ministry of Water Resources of Nigeria in the reformulation of the updated NWRMP (JICA 2012).

**METHODS**

Nigeria’s landscape is highly diverse, with mountains in the southeast, hills and plateau in the center, lowlands in the south, and plains in the north (Figure 1(a)). The country is well drained with a network of rivers and streams. Some of the rivers, particularly small ones in the north, are seasonal due to the shorter duration of the rainy season (Ayoade 1975). There are three major water systems in Nigeria: the Niger River that flows north west, its main tributary, the Benue River, in the east, and Lake Chad in the north east. Secondary water systems are littorals along the coasts.

To support adequate management of water resources, Nigeria and its water systems are divided into eight territorial domains named hydrological areas (HAs; Figure 1(b)). Assessment of climate risk on spatial and temporal availability of water resources for each HA was performed using the GIS implementation of the SWAT model (ArcSWAT; http://swatmodel.tamu.edu/software/arcswat) suitable for making physically based and spatially explicit simulations of the water balance (Neitsch et al. 2002).

The model divides a watershed into sub-basins and smaller homogeneous units known as hydrologic response units (HRUs), characterized by unique features of morphology, land cover, and soil. In other words, HRUs have specific characteristics in terms of their reaction to water balance processes.

Furthermore, the model requires integration of specific data for water budget simulation. In particular, the model is based on spatial (digital elevation model (DEM), stream network data, land use, and soil maps) and non-spatial data, related to meteorological and discharge observations.

As for spatial data, besides information on elevation and land cover, soil attributes are classified into structural (e.g., texture, gravel content), physical (density), biological (e.g., carbon content) and hydrological (e.g., hydraulic conductivity, available water content) characteristics of soil units.

Meteorological data consist of precipitations, daily maximum and minimum temperature, solar radiation, wind speed, and relative humidity. Discharge data are essential for sensitivity analysis of model parameters as well as for model calibration and validation purposes.

The model output selected as the impact variable representative of water availability is the water flow (hereafter water yield; WYLD according to the ArcSWAT terminology), expressed as the annual sum of surface flow and return flow from the shallow groundwater.

Once ArcSWAT calibration and validation were performed along the chosen historical period 1976–2005 and for selected locations according to the temporal and spatial availability of data, the impact analysis covered the entire country at sub-basin level and consisted of an ensemble of ten hydrological simulations driven by the same number of climate projections under A1B emission scenario, falling at the middle among the extreme IPCC storylines.

More specifically, first the regional climate model (RCM hereafter) COSMO-CLM (Rockel et al. 2008) was run for Nigeria at about 8 km spatial resolution for the period...
1971–2065. Boundary conditions were set by the CMCC-MED model (Scoccimarro et al. 2011) run at about 80 km resolution. Further, to capture the comprehensive range of probable future climate outcomes, maintain high spatial resolution, and address uncertainty about future climate, nine climate projections from Global Circulation Models (GCMs, taking part of the well developed CMIP3 experiment; http://cmip-pcmdi.llnl.gov/cmip3_overview.html) were used to ‘perturb’ RCM results for the medium-term future period 2036–2065. Before perturbation, RCM data were bias-corrected via comparison with the most recent observational CRU dataset (http://www.cru.uea.ac.uk/cru/data/hrg/; Mitchell & Jones 2005) over the same historical period.

Perturbation was based on the spatial monthly anomaly generated through GCMs. For temperature perturbation, a
monthly anomaly based on the difference between future and historical GCMs was added to daily values from the RCM. For precipitation, the scaling factor applied to the daily amount from RCM simulation was the ratio between monthly future and historical GCMs (Buishand & Lenderink 2004). Table 1 lists the GCMs chosen for this simulation.

Results on WYLD were analyzed by comparing 30-year averages over the medium-term future period (2036–2065) with the baseline (1976–2005) taken as reference scenario (no climate change).

Starting from impact results, and assuming the water demands for irrigation under development targets expected by the government are met, the uncertainty analysis about future climate change may suggest containing (or increasing) the storage size, when wetting (or drying) is expected in the future, in terms of mean climate and duration of low flow periods. Indeed, in the case of climate change, a given storage designed upon historical data may receive less (more) water than expected and produce less (more) benefits than projected.

Of course, adapting the design of new reservoirs to match a future climate change is accompanied by a certain adaptation cost, including the extra capital cost of building storage. The cost becomes negative if less storage is to be built compared with the design under the historical climate.

In the following section on model setup, calibration, validation and application for impact analysis and robust decision-making are described in detail.

### Model setup

#### Spatial inputs

The DEM is used within ArcSWAT for dividing the application domain into physiographic units. The last version of the DEM processed from the SRTM (http://www.cgiarcsi.org/data/srtm-90m-digital-elevation-database-v4-1) and resampled to 1 km resolution (Figure 1(a)) was used to extract the river network and divide the Nigerian territory into 893 hydrologically connected stream reaches and correspondent sub-basins and HAs (Figure 1(b)). To this aim, the most reliable terrain analysis procedures (TauDEM, Tarboton et al. (1991), Tarboton (1997)) have been used, eliminating the known limits of the standard methods implemented in the majority of GIS-based hydrological tools (Nardi et al. 2008).

For each sub-basin, a set of topographic statistics was calculated by ArcSWAT (e.g., mean slope, stream length, etc.). The slope was classified into five classes: (1) slope < 1.14%, (2) 1.14 ≤ slope < 4.18, (3) 4.18 ≤ slope < 9.89, (4) 9.89 ≤ slope < 16.64, (5) slope ≥ 16.64. These units were extracted from the slope frequency distribution using a Jenks Natural Break Algorithm, which seeks to reduce the variance within classes and maximize the variance between classes.


The combination of the two land cover maps consisted first in resampling their original resolution of 500 m (MOD2005) and 300 m (GLC2006) to 1 km. The ‘majority’ algorithm in ArcINFO was chosen to associate the most frequent land cover coming from original pixels at finer resolution to each ‘new’ pixel at 1 km resolution. Then, a SWAT land cover class was associated with each IGBP land cover class, as depicted in Table 2. The IGBP ‘cropland/natural vegetation mosaic’ was further

<table>
<thead>
<tr>
<th>Table 1</th>
<th>List of GCMs used to perturb RCM outputs for the future period from 2036 to 2065</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>Res. (lat. × lon.)</td>
</tr>
<tr>
<td>HadCM3</td>
<td>2.5′ × 3.75′</td>
</tr>
<tr>
<td>CGCM_2.3.2</td>
<td>2.8′ × 2.8′</td>
</tr>
<tr>
<td>CNRM_CM3</td>
<td>2.8′ × 2.8′</td>
</tr>
<tr>
<td>CSIRO_Mk3.5</td>
<td>1.9′ × 1.9′</td>
</tr>
<tr>
<td>CCSM3</td>
<td>1.4′ × 1.4′</td>
</tr>
<tr>
<td>MIROC3.2</td>
<td>1.125′ × 1.125′</td>
</tr>
<tr>
<td>GFDL_cm2.1</td>
<td>2.5′ × 2′</td>
</tr>
<tr>
<td>ECHAM5</td>
<td>1.875′ × 1.875′</td>
</tr>
<tr>
<td>FGOALS</td>
<td>2.8125′ × 2.1825′</td>
</tr>
</tbody>
</table>
detailed using GLC2006 (Table 3). This cross-merging also allowed reduction of the number of non-classified pixels.

Concerning soil, the majority of the attributes necessary for the ArcSWAT model were derived from the best presently available dataset, the HWSD (Harmonized World Soil Data-set; http://www.iiasa.ac.at/Research/LUC/External-World-soil-database/HTML/) at 1 km resolution. Soil hydraulic conductivity, albedo and erodibility, were parameterized from Saxton & Rawls (2006), Ten Berge (1986), and SWAT documentation (http://www.ars.usda.gov/Research/docs.htm?docid=6028), respectively. Finally, each sub-basin was divided into distinctive 15,338 HRUs.

### Non-spatial inputs

Meteorological data should be inserted for computing the water balance in ArcSWAT. For this purpose, according to the reliability of position for the measurement stations after cross-checking their coordinates between NIMET and NCDC (http://www.ncdc.noaa.gov/cdo-web/) datasets, 29 stations for rainfall and temperature (minimum and maximum) were selected (Figure 2).

The daily series of rainfall and minimum/maximum temperatures were used in the ArcSWAT model for calibration/validation. Given significant gaps in such records, the weather generator available in ArcSWAT was first set up for filling the gaps. A weather generator was also set up for simulating wind, relative humidity, and solar radiation at 23 sites across Nigeria from CLIMWAT2.0 dataset (http://www.fao.org/33880/02c13815.pdf) and matching with locations of precipitation/temperature observations.

<table>
<thead>
<tr>
<th>IGBP Land cover</th>
<th>SWAT Land cover</th>
</tr>
</thead>
<tbody>
<tr>
<td>Evergreen needleleaf forest</td>
<td>Evergreen forest</td>
</tr>
<tr>
<td>Evergreen broadleaf forest</td>
<td>Evergreen forest</td>
</tr>
<tr>
<td>Deciduous needleleaf forest</td>
<td>Deciduous forest</td>
</tr>
<tr>
<td>Deciduous broadleaf forest</td>
<td>Deciduous forest</td>
</tr>
<tr>
<td>Mixed forests</td>
<td>Mixed forest</td>
</tr>
<tr>
<td>Closed shrublands</td>
<td>Range shrubland</td>
</tr>
<tr>
<td>Open shrublands</td>
<td>Range shrubland</td>
</tr>
<tr>
<td>Woody savannas</td>
<td>Pasture/hay</td>
</tr>
<tr>
<td>Savannas</td>
<td>Pasture/hay</td>
</tr>
<tr>
<td>Grasslands</td>
<td>Grasslands/herbaceous</td>
</tr>
<tr>
<td>Permanent wetlands</td>
<td>Woody wetlands</td>
</tr>
<tr>
<td>Croplands</td>
<td>Generic crops</td>
</tr>
<tr>
<td>Urban and built-up</td>
<td>Urban medium density</td>
</tr>
<tr>
<td>Cropland/natural vegetation mosaic</td>
<td>See Table 3</td>
</tr>
<tr>
<td>Snow and ice</td>
<td>Not classified</td>
</tr>
<tr>
<td>Barren or sparsely vegetated</td>
<td>Not classified</td>
</tr>
</tbody>
</table>

### Table 3 | Reclassification of the GLC2006 layer (in case of the IGBP class ‘cropland/natural vegetation mosaic’) according to the SWAT land cover classification

<table>
<thead>
<tr>
<th>GLC2006 Land cover</th>
<th>SWAT Land cover</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rain-fed croplands</td>
<td>Generic crops</td>
</tr>
<tr>
<td>Mosaic croplands (50–70%)/vegetation (grassland/shrubland/forest) (20–50%)</td>
<td>Generic crops</td>
</tr>
<tr>
<td>Mosaic vegetation (grassland/shrubland/forest) (20–50%)</td>
<td>Range shrubland</td>
</tr>
<tr>
<td>Closed to open (&gt;15%) broadleaved evergreen or semi-deciduous forest (&gt;5 m)</td>
<td>Mixed forest</td>
</tr>
<tr>
<td>Open (15–40%) broadleaved deciduous forest/woodland (&gt;5 m)</td>
<td>Deciduous forest</td>
</tr>
<tr>
<td>Mosaic forest or shrubland (50–70%)/grassland (20–50%)</td>
<td>Range shrubland</td>
</tr>
<tr>
<td>Mosaic grassland (50–70%)/forest or shrubland (20–50%)</td>
<td>Grasslands/herbaceous</td>
</tr>
<tr>
<td>Closed to open (&gt;15%) (broadleaved or needleleaved, evergreen or deciduous) shrubland (&lt;5 m)</td>
<td>Range shrubland</td>
</tr>
<tr>
<td>Closed to open (&gt;15%) herbaceous vegetation (grassland, savannas or lichen/mosses)</td>
<td>Grasslands/herbaceous</td>
</tr>
<tr>
<td>Sparse (&lt;15%) vegetation</td>
<td>Grasslands/herbaceous</td>
</tr>
<tr>
<td>Closed to open (&gt;15%) broadleaved forest regularly flooded (semi-permanent or temporarily) – fresh or brackish water</td>
<td>Woody wetlands</td>
</tr>
<tr>
<td>Closed (&gt;40%) broadleaved forest or shrubland permanently flooded – saline or brackish water</td>
<td>Woody wetlands</td>
</tr>
<tr>
<td>Closed to open (&gt;15%) grassland or woody vegetation on regularly flooded or waterlogged soil – fresh, brackish or saline water</td>
<td>Emergent/herbaceous wetlands</td>
</tr>
<tr>
<td>Artificial surfaces and associated areas (urban area &gt;50%)</td>
<td>Urban medium density</td>
</tr>
<tr>
<td>Bare areas</td>
<td>Not classified</td>
</tr>
<tr>
<td>Water bodies</td>
<td>Water</td>
</tr>
</tbody>
</table>
In addition, streamflow data are vital for calibration and validation of the model, as the simulated monthly series of water flow can be compared with observed monthly streamflow records at the chosen locations.

Extended research on discharge information was performed to analyze datasets from different sources, i.e., IWRMP (Integrated Water Resource Management and Planning) project, the hydrological year books from the Nigerian Hydrological Service Agency (NIHSA), and the NWRMP (JICA 1995). The last source is the most complete in terms of HAs and time coverage (including 89 stations for different time intervals over the 1960–1989 period) and was taken as the basis for selecting suitable stations for sensitivity analysis, calibration and validation of the model. Locations of discharge stations are presented in Figure 2.

**Model calibration and validation**

During calibration and validation steps, several limitations have been recognized. First, in many cases, the station (both meteorological and hydrological) position is uncertain with coordinate precisions of 1 arc-minute, causing inaccuracy in data. Second, available meteorological stations closest to the sub-basin, as used by ArcSWAT, are often located rather far (even downstream) from the streamflow stations. In other words, meteorological stations could not be representative of the rainfall–runoff spatiotemporal dynamics. Third, some constraints were due to different time frames covered by precipitation (1975–2009) and stream flow (1960–1989) station data, including large temporal gaps (inter- and intra-annual) and lack of quality flag/information about data reliability.

Under the above restrictions, streamflow data for stations functioning for a short period of time and therefore having diffuse intra- and inter-year gaps, stations not located along river networks and dam stations were excluded from calibration/validation analyses. Therefore, five sub-basins (representative of the equal number of HAs) were considered suitable for the model (Figure 2).

The above-mentioned limitations also affected the choice of parameters to be calibrated. There are more than 60 parameters in the SWAT model, which vary by sub-basin, land use, or soil type, further increasing the number of parameters. As the calibration was possible for selected sub-basins according to the streamflow station best-estimated positions, it also limited the number of parameters to the ones strictly related to the runoff and superficial-shallow soil water dynamics (e.g., no management or deep-groundwater

![Figure 2](https://example.com/figure2.png)
parameters could be considered as no detailed spatialized data were available for their calibration).

Sensitivity analysis was the first step of the calibration procedure to select the parameters for adjustment. Considering the focus of this study on water availability as well as the wide spatial extent of the analysis, constraining to cross-assumptions and assimilations among sub-basins, and considering the work of van Griensven et al. (2006), the first five top-rated sensitivity parameters were considered as highly important (n. 1) and important (n. 2–5). For calibration purposes, the capability of the SWAT-CUP30 software package, in general, and the SUFI2 module, in particular, were exploited, following procedures in Schuol et al. (2008), whose study area covered Nigeria.

Table 4 shows how, although with slightly different ranking, the most sensitive parameters were confirmed across HAs, supporting the findings of Schuol et al. (2008). The 10th–90th percentile final ranges of parameter values are displayed in Table 4.

Discharge data for at least half of the available periods were used for calibration, while the remaining years were used for validation purposes. Considering the moderately stringent model quality requirements $P$-factor >60% and $R$-factor <1.3 as in Schuol et al. (2008), four out of five sub-basins respected at least one requirement, while three out of five sub-basins respected both requirements. Given the limits discussed above, a further reduction in parameter uncertainty was considered not reasonable.

Parameters were associated with each of the non-calibrated sub-basins relying on those of the calibrated sub-basin with the most similar characteristics in terms of HRU attributes (i.e., combined slope, land cover, and soil).

### Impact analysis

The model was applied at daily time steps first for the baseline using the RCM output and then for the future period using the RCM and its nine perturbations for precipitation and temperatures. Outputs were aggregated at 30-year periods. The analysis was based on comparison of each 30-year future period (2036–2065) simulated under the ensemble of all climate projections to the baseline (1976–2005). Inflows to the Niger and Benue rivers from outside Nigeria were assumed unchanging due to their lack of influence on planning for irrigation development.

### Robust decision-making

The storage requirement for irrigation purposes is a function of the variability of the water runoff. To achieve a yield close to the average runoff, the storage must be large enough to handle the largest flood flow and to support releasing water through the longest and deepest drought. Monthly inflow series from the hydrological analysis at sub-basin level allowed calculation of storage yield curves (SYCs) for each sub-basin, indicating the storage capacity needed to provide a given basin yield or, alternatively, the firm basin yield produced from a given level of storage. SYCs were built with reference to Sequent Peak Algorithm (SPA; Thomas & Burden 1965) designed for studying reservoir capacity. SYCs are useful to consider the combined effect of annual flow amount and inter-annual variability for a hypothetical reservoir put at the outlet of each sub-basin.

Working at the country-wide level, ‘local’ rather than ‘cumulated’ storage requirements were addressed, assuming

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Most frequent ranking</th>
<th>Final range</th>
</tr>
</thead>
<tbody>
<tr>
<td>GWqmn</td>
<td>Threshold depth of water in the shallow aquifer required for return flow (mmH$_2$O)</td>
<td>1</td>
<td>540–820</td>
</tr>
<tr>
<td>CN2</td>
<td>Curve number</td>
<td>3</td>
<td>10–89</td>
</tr>
<tr>
<td>ESCO</td>
<td>Soil evaporation compensation factor</td>
<td>2</td>
<td>0.15–0.85</td>
</tr>
<tr>
<td>GW_revap</td>
<td>Groundwater ‘revap’ coefficient: regulates the movement of water from the shallow aquifer to the root zone</td>
<td>5</td>
<td>0.04–0.17</td>
</tr>
<tr>
<td>ALPHA_BF</td>
<td>Baseflow alpha factor</td>
<td>4</td>
<td>0.32–0.98</td>
</tr>
</tbody>
</table>
that each sub-basin (as defined by river stream order hierarchy; Strahler 1952) is self-sufficient in providing water for its own ‘internal’ irrigation needs.

Successively, SYCs for historical and future periods were analyzed together with assumptions of storage costs and a projected water demand for irrigated areas.

The storage building costs for the years from 2012 to 2015 have been estimated with the method described in Ward et al. (2010), i.e., using relationships between slope and construction costs per cubic meter according to the size class of reservoirs. Operation and maintenance costs for each of the 50 y from 2016 to 2065 were estimated at 2% of the capital cost (Ward et al. 2010). Costs for African countries such as Nigeria are assumed to be 68.5% of US costs (Kirshen 2007).

The irrigation demand was estimated first by aggregating per sub-basin total cultivated areas in 2000 from the MIRCA database (Portmann et al. 2010). Different estimates on the actual extension of irrigated lands in Nigeria are outlined below:

- AQUASTAT-FAO reported irrigated area was 219,838 ha in 2004;
- statistics from MIRCA dataset emphasized that irrigated croplands are 157,711 ha;
- nation master statistics (http://www.nationmaster.com/red/country/ni-nigeria/agr-agriculture&all=1) referred to 259,140 ha;

The average value obtained from the above sources was calculated as 232,422 ha.

Irrigated area hectares in the medium term are projected for each sub-basin, under VN20, as 25% of the cultivated area. The amount of irrigated area was considered plausibly stable starting with the year 2020 when the VN20 target is met (or 2025, if the ‘prudential’ view of VN20 is considered), to 2050.

Water used in irrigated agriculture in Nigeria is estimated at about 1,087 × 10^6 m^3/year (Mekonnen & Hoekstra 2010, Appendix IV). The annual Crop Water Requirement (CWR) for irrigated agriculture can be roughly estimated as 1,087,000,000 m^3/232,422 ha = 4,700 m^3/ha.

By multiplying annual CWR per irrigated hectares in 2050, the projected annual water demand was first calculated, and then the necessary storage from SYCs was identified, again for each sub-basin. Finally, the opportunity range of avoiding costs of storage was examined.

**RESULTS AND DISCUSSION**

The map in Figure 3 illustrates, for each sub-basin, the sign of deviation from the national average of WYLD along the baseline period, being 600 mm/year per land unit (i.e., equal to 100%). The spatial homogeneity is evident where the central plateau and the wet south (coastal areas) are above the national average, while the arid north and the uppermost Niger and Benue reaches present WYLD below the national average.

Since hydrological simulations tend to disagree on the amount of expected change in water flow, the model results were summarized by defining four classes of risk. Using ±15% as a stability band of percent changes with respect to historical averages, a given sub-basin is considered ‘stable’ if most simulations (i.e., those falling within the range of the 1st to the 99th percentiles of the ensemble) agree that future water flows will not be larger than 15% of historical values, nor will they be less than –15%. Sub-basins are considered exposed to ‘dry risks’ if the 1st percentile is less than –15% and the 99th percentile is less than 15%; to ‘wet risk’ when the 99th percentile of changes is larger than 15% and the first percentile is more than –15%; and are considered uncertain when projected decline and increase are lower than –15% and larger than +15%, respectively.

Tones in Figure 4 describe the consensus among climate models on whether such a stability band is likely to be exceeded by mid-century. For water planning purposes, a change between ±15% in historical WYLD is considered equivalent to stable conditions (mid-gray tone). Light gray areas indicate sub-basins where most models agree on an increase in WYLD. In dark gray areas, the consensus is on a decrease in WYLD. White color indicates uncertain sub-basins, where consensus is not evident and models simulate both an increase and a decrease of WYLD larger than 15%.
Comparing 1990 and 2050 (representative of 1976–2005 and 2036–2065, respectively), the situation is projected spatially heterogeneous in terms of water availability, with 43% of the area under wetter conditions (representing 34% of runoff), 13% under drier conditions (21% of runoff), 13% stable and 31% uncertain (31 and 14% of runoff, respectively).

It is noteworthy to mention that there is a high uncertainty for northern arid/semi-arid regions, reflecting general findings on the rainfall uncertainty from previous
global climate simulation ensembles (IPCC 2007). Results for the central plateau, southeast mountains, and southwest littoral indicate a general drying trend from 1990 to 2050.

The finding that in 2050 about half of the country is projected to experience an increase in water flows is relatively robust to the selection of the stability band (Figure 5). While the share of territory decreases to 30% for a stability band of ±10%, it fluctuates only slightly around 45% for bands of ±15, 20, and 25%. The share of land subject to uncertainty decreases in the case of wider stability bands; and the share of land area exposed to ‘dry’ risks varies between 2 and 14% (from 2 to 27% in terms of historical flow), depending on the stability band selected.

It is important to mention that almost half of Nigeria may expect an increase in water flows by 2050. Figure 6 plots the largest (99th percentile) projected flow increase for wet risk sub-basins in 2050 against relative size of flow in each basin (expressed as a fraction of the mean national flow, as illustrated in Figure 3).

The largest relative increases of flow (>30%) are projected to take place in drier basins, i.e., those under the average flow of 600 mm/year across Nigeria, representing less than 28% of the sub-basins and 32% of the national area. While flow is projected to increase up to 200% in some cases, the weighted average of increases remains under 38%.

The study also revealed that all sub-basins showing a prevalent dry risk are included among those with actual water flow above the national average.

Analyzing impacts as a combination of mean changes and variability in inflow is a more efficient way to identify drying or wetting trends and to estimate effective water availability. Indeed, in the case of reduced (increased) range of flows, more (less) yield is possible from a given hypothetical storage capacity. The analysis performed via SYCs allowed consideration of not only average conditions but also water flow variability in climate risk assessment.

Assuming the irrigation area demand for each sub-basin under VN20 as 25% of cultivated lands and excluding sub-basins assumed with ‘uncertain’ behavior in terms of water flow...
WYLD, storage cost changes projected under different future climates with respect to the historical period have been averaged. In most cases, Nigeria is expected to receive more water in the climate change scenarios tested than in the baseline scenario. Results in Figure 7 highlight the ample opportunity of avoiding or reducing costs from storage oversizing across the main part (82%) of the ‘not-uncertain’ (in terms of WYLD) Nigerian territory, representing 57% of the country. In addition, for 18% of the ‘not-uncertain’ area (12% of the country) costs of storage to reach irrigation targets are likely to be higher in the future compared with the design based on historical climate. Practically, 57 and 12% represent the portions of the country with the risk of over- and under-investing, respectively, when neglecting the potential future climate trends.

Although the approach adopted in this study is significantly simplified, results confirm that interpreting imprudently increased annual average water availability as wetter conditions is misleading. Inter- and intra-annual variability cannot be neglected when referring to wetter or drier conditions and for planning the storage and use of available water. This fact explains why several basins in the center of Nigeria, while expected to deliver more runoff than in the past, will likely experience less yield under a given storage and, therefore, require larger investments. Equally, the southeast plateau seems to suffer from an overall drying in the future, but with less flow variability that allows foreseeing lower costs.

Using historical climate records as a basis for determining the adequate size of investment in water storage may lead to ‘regrets’. Excessive storage and investment are probable in the case of a wetter future not being taken into account, whereas insufficient yield may occur in the case of an unaccounted for drier future, causing losses in crop production. Similarly, in the case of known storage volume, under-sizing the area equipped for irrigation under a wetter future could represent a missed opportunity to irrigate a larger area and production of more crops, while over-sizing the irrigation scheme under a drier future could lead to crop production gaps.

In addition to positive direct effects on cost reduction and/or food security by preserving agricultural productivity, the proposed methodology has the potential to support robust decisions and more coherent allocation of financial resources, allowing capital to be saved for investment in more drought-resistant crop varieties or other strategies to adapt Nigerian agriculture to climate change.

SYC analysis also suggests that for sub-basins where no more yield can be obtained from the current level of runoff, if more water is needed, it must be transferred from another
CONCLUSIONS

The preceding sections have provided an illustrative picture of what may happen to runoff and reservoir yield under combined precipitation and temperature changes in Nigeria. Irrigation is of primary importance to baseline sector development and, thus, can play an important role in climate change adaptation for agriculture, entailing large capital expenditures (with unit costs often higher in Nigeria than in comparative countries). This work has explored the application of a ‘robust decision-making’ approach to enhance the resilience of irrigation development to climate change. Indeed, adequate sizing of any given irrigation scheme (primarily the size of hypothetical reservoirs for larger schemes based on dams) depends on the climate expected to prevail in the future.

However, disagreement among climate models on precipitation projections makes it difficult to estimate how much water could be available in the future for irrigation, hydropower, and municipal water supply. Lack of agreement in studies makes planning and design challenging, since it is not known at present which climate will unfold in the future. Uncertainty in the future can be reduced by considering an ensemble of climate projections and associated water budget, investigating the degree of consensus among ensemble members and then classifying a given outcome as more or less probable.

Irrespective of the climate scenario considered, water available for storage and use in the future will be different than it was in the past. Climate-driven hydrological simulations converge in projecting an increase in water flows for almost half the country by mid-century. Consensus is apparent for a decrease of water flows in 13% of the country, and for uncertain conditions in one-third of Nigeria’s surface. Stable conditions are projected in 13% of the national territory.

Although it is essential that attention is paid to this issue to further prepare the country for future climate changes, given the global experience with inappropriate water management, the results presented in this study should be considered prudent and mainly purposeful of a valuable methodology, while not misleading to a false idea of increased water availability and, thus, of economic hope for Nigerian agriculture.

Indeed, not only mean annual runoff should be integrated into evaluation of water availability, but also variability of inflow should be taken into account. For any given area to be irrigated, unexpected drier conditions – in terms of combined mean annual inflow and variability – may require more storage than those designed for a wetter climate. Similarly, if not taken into account, even unexpected general wetter conditions, requiring less capital cost for storage, can have negative outcomes for the national economy largely dependent on agriculture.

There is an emerging consensus that almost two-thirds of the country, using the climate of the past as a guide to design future water management projects, may suffer from inappropriate investment decisions which do not allow capital saving or the exploitation of opportunities. More specifically, the proposed approach showed that for more than half of Nigeria’s territory investment costs for storage could be avoided in the presence of more detailed knowledge about the most likely future climate change. In about 12% of the country, under-investments could be avoided, while the remaining part seems to be affected by inflow uncertainty.

Optimizing capital investments in any direction is an essential step for appropriate allocation of financial resources to undertake alternative actions for water supply (e.g., inter-basin water transfer) and/or to implement additional climate change adaptation strategies in agriculture supporting food security and development goals.

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