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ORIGINAL ARTICLE

Spatial modelling of present and future groundwater potentials in Nigeria; towards a sustainable water demand and supply

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Abstract

The development of water resources in Nigeria has not risen alongside population increase. Although groundwater is the available source of water at all locations in Nigeria, groundwater aquifer is becoming deeper due to increased groundwater harvest, especially in urban areas. There is a need for continuous groundwater modelling using geological, climatic, environmental data, and spatial tools especially under climate change and intense landcover conversions. The Spatial Multi-Criteria Analysis (SMCA) was adopted in this study to model the current groundwater potential in Nigeria. The multi-criteria analysis tool in ArcGIS was explored to overlay the nine factor maps to model historic and futuristic groundwater potentials. Our groundwater factor maps show an interesting pattern across Nigeria, the southern parts show more potential considering suitability factors like; surface water density, rainfall, temperature, soil, land cover and elevation in the region. Whereas the upland regions even with higher rainfall and lower temperatures suitable for groundwater recharge, are disadvantaged by geomorphological factors. Northern part of Nigeria shows high potentials, considering the geology, soil, lineament density and slope, but disadvantaged by other factors like lower rainfall and higher temperatures. This informed the final groundwater potential maps; results for the historic potential revealed that, no location in Nigeria has optimal (9–10), very poor or no (1–2) groundwater potential. The results further revealed that areas with higher groundwater potentials are largely within the corridors of major rivers in Nigeria (Niger and Benue), covering about 17.6% of the Nigerian landmass, while 2.6%, 33.7, 44% and 2.2% are occupy areas with very low, low, moderate and very high groundwater potentials respectively. Further analysis highlighs locations of concern due to climatic and environmental changes. Interestingly, our groundwater projection results show a persistent increase in groundwater potential from 2021 to 2100 if current landuses and environmental factors are maintained, and if the projected increase in rainfall is true. Despite these groundwater potentials, the recent issues of shallow aquifers have been cautioned by scientists, especially due to groundwater uncertainties in Nigeria especially with intense landcover conversions, combined with accelerated water demands due to increase in population, and incessant groundwater extractions. Therefore, there is a need to seek caution in the pattern of unregulated and incessant groundwater harvest in Nigeria and we recommend frequent updates of the groundwater potential using geospatial tools to inform governing policies on a centralised consolidated sustainable water supply in Nigeria.

Keywords Remote sensing · Climate change · Geospatial · Multi-criteria · Projections · Sustainable

Introduction

Globally, water resources are unevenly distributed and water demand has never been fully met. Therefore, water resources and demand are unbalanced, with a water ratio of 1.6% in 2010, but expected to reach 4.4% by the year 2030, which implies that the total water demand in 2030 will still be lesser than the total potential water resources (JICA 2014).

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Presently, an estimated 783 million people have yet to have access to clean drinking water (UNICEF and WHO 2012). About 70% of water consumption (surface and groundwater) is attributed to agriculture, while municipal and industrial water consumption accounts for the remaining 30% (OECD 2012). Most of the communities with poor access to water are within sub-Saharan African (SSA) countries (Omole 2013). While JMP (2010) reported that, over 300 million people in Africa are without access to safe drinking water and typically the poorest and most vulnerable in the world.

Reports are that four out of every ten persons in SSA are without access to clean water (UNICEF and WHO 2012). About 50% of the world's population access portable water from groundwater sources (IIED 2010). While about 75% of the population in SSA depends on groundwater for potable water (AWV 2009; IIED 2010).

Water distribution in Nigeria shows a rather disturbing trend, with only 14% of the population having regular pipe water supply and 86% of the remaining population depending on direct surface and groundwater sources for their water needs (JICA 2014). Groundwater has better water quality for human and animal consumption compared to surface water (JICA 2014). Groundwater was discovered in Nigeria around 1928, and with credit to the Nigerian Geological Survey (NGS), hand-dug wells were introduced in Nigeria since then and have remained the major technique across the country. However, by the year 1938, the NGS upgraded the groundwater harvesting technique to drilled wells (Omole 2013). Nigeria like many SSA countries is blessed with a large groundwater resource but unevenly distributed (Edet et al. 2011). Rijswljk (1981) estimated the total groundwater potential in Nigeria to be $6 \times 1018\ m^3$. It was estimated that about 60% of Nigeria's population access water from ground resources. However, groundwater harvest is carried out on individual capacities due to infrastructural decay in the water supply sector and lacking government commitment and policies in Nigeria. Groundwater is accessed from both shallow hand-dug wells and deep boreholes. There have been several reports that this action has become one of the most unregulated activities in Nigeria, with rapid urbanization, this has drastically increased with cheaper drilling technologies (Omole 2013). Regrettably, to our knowledge, there are limited explicit scientific efforts in current literature on the constant spatial monitoring of groundwater quantity and quality in Nigeria, integrating environmental data, and climate, especially irregular rainfall patterns and increased temperature at both local and national scales. This information is regularly required to adapt to a growing water demand associated with population growth and climate variability in different environments across Nigeria, especially at the current level of reported excessive and unregulated groundwater extraction and landcover changes.

Remote sensing and other geospatial tools like Spatial Multi-Criteria Analysis (SMCA) and mathematical models are applied in general water resource management (Chuma et al. 2013; Iftikhar et al. 2016; Ochir et al. 2017; Daffi et al. 2020; Ibrahim et al. 2020; Ugese et al., 2022). Adelana and MacDonald (2008) first produced the groundwater potential maps of the African continent. Then MacDonald et al. (2012) under the program of the British Geological Survey (BGS) water aid in Africa produced the first quantitative maps of groundwater storage and potential groundwater yields for Africa. They modelled specifically groundwater productivity, storage and depth in Africa based on the saturated aquifer thickness, using geological features, elevation and effective porosity. The groundwater depth, in particular, was modeled using a spatial empirical rules-based approach, built on rainfall, geomorphology/weathering aquifer type and proximity to rivers. They tested different modeling approaches in estimating groundwater and recommended the rule-based approach in GIS. Their results show that many African countries have appropriate groundwater that can sustain water needs, with total groundwater storage potential, estimated to be about 0.36–1.75 million km^3. Their estimated potential groundwater storage for Nigeria is 5710–33600 km^3.

In the Nigerian context, groundwater monitoring in the past was solely based on the hydrogeological factor (Okereke et al. 1998; Ofodile 2002; Christopher et al. 2003). Not taking into account that while geological compositions and soil types are static factors, climatic factors and landcover are changing parameters. JICA (2014) brought to view that groundwater potential is the groundwater recharge capacity, the maximum amount of groundwater to be developed based on certain geological, climatic and environmental factors. Therefore, groundwater potential in Nigeria cannot remain static especially now under both climate change and intense landcover conversions, and this is already reported in some high-potential areas where groundwater aquifers are reducing (Mekwunye 2013). Recently Geographic Information System (GIS) and remote sensing tools have also been tested in Nigeria to estimate groundwater using SMCA even though on a small local scales (Ahmed et al. 2017; Adeyeye et al. 2018; Sikakwe 2018; Epuh et al. 2020; Nwosu et al. 2020), and sub-regional scales (Fashae et al. 2014; Akinluyi et al. 2021). There is a need for consistent groundwater monitoring and comparison at a national scale considering the recent changes in climates, landcover, and environments. To address this gap, we have tested the capabilities of GIS, SMCA tools and Remote Sensing to model both historic-current and future groundwater potentials in Nigeria with the integration of land cover features, soil, geological, climatic and environmental data. This method can be updated regularly for appraising groundwater potentials and other related problems. In this article we also highlighted regional surface and groundwater distribution in Nigeria and also compared with areas of water demands and accessibility in Nigeria.

Materials and methods

Study area

Nigeria lies on latitudes 4° and 15° North of the Equator and latitudes 3° and 14° East of the Greenwich Meridian. Nigeria shares land borders with the Republic of Benin on the

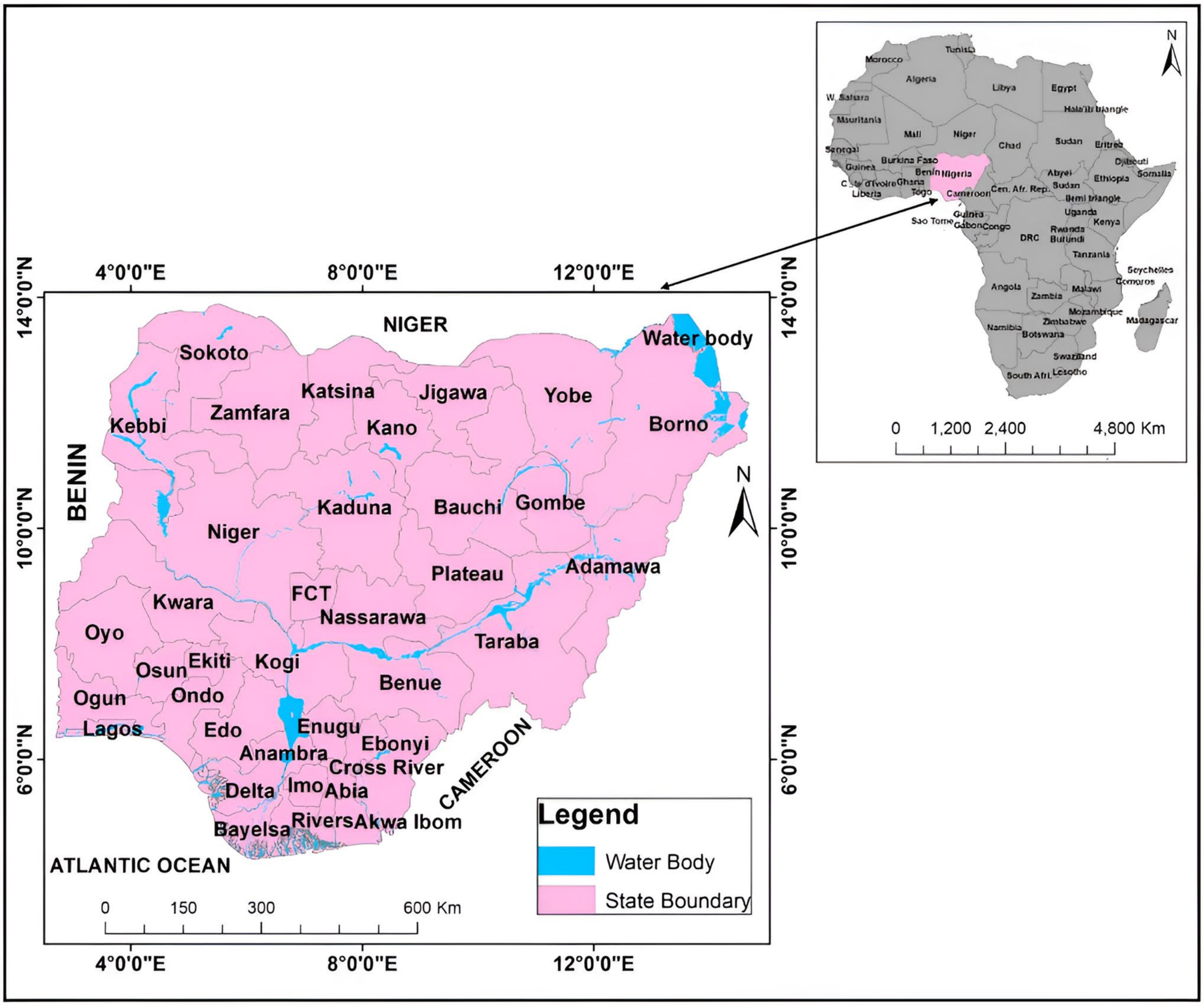

Fig. 1 Geographic location of Nigeria (Study Area)

west, Niger Republic in the North and Chad and Cameroon on the Eastern border (Fig. 1). The Nigerian coast lies on the Gulf of Guinea in the South and it borders Lake Chad to the North-Eastern region (Fig. 1). Nigeria is the sixth most populous country in the world with a population of approximately 223 million in 2023 (accessed from: https://www.unfpa.org/data/world-population/NG; accessed on 20 April, 2024). The population factor has a direct effect on water demands. This is even more pressing with an estimated growth rate of 2.6% annually and estimations reaching 320 million people by 2060 (Omole 2013), which is one of the largest population growth rates in the world.

Nigeria occupies a landmass of 923,768 km^2 (The World Atlas 2015), with about eight distinct ecological regions namely; humid forest, derived savannah, southern guinea savannah, northern guinea savannah, Sudan Savannah, Sahel Savannah, and mid altitude (Babatunde 2017). Nigerian climate, elevation, land cover, geology, soil, slope, fault lines and so on are shown and described in the subsequent sections below.

Data and pre-processing

Groundwater potential was modelled combining several environmental factors using the SMCE modelling techniques in ArcGIS version 10.5. The data used for this study are shown in Table 1 below. The vector data (surface water, soil, and geology) were converted to raster format, all data were re-projected as geographic WGS 84 (EPSG 4326) and the spatial resolution resampled to 30 m for conformity.

Table 1 Data description

Data Type	Derivable	Source	Scale/Resolution	Date
Rainfall	Rainfall	https://www.worldclim.org/data/cmip6/cmip6_clim10m.html	250 km^2	1970–2100
Surface water	Streams and Rivers,	National Space Research and Development Agency (NASRDA)	1:50,000	2017
Temperature	Temperature	https://www.worldclim.org/data/cmip6/cmip6_clim10m.html	250 km^2	1970–2100
Landcover	Landcover	European Space Agency (ESA) GlobCover 2.3	20 m	2009
Shuttle Radar Topographic Mission (SRTM)	Elevation and slope	Global Land Cover Facility (GLCF)	30 m	–
Administrative Boundaries	LGA	Open Street Map	1:250,000	2005
Soil map	Soil Type	FAO	1;100,000	1990
Geology Map	Geology	Nigerian Geological Survey (NGS)	1:500,000	2006
Lineament	Fault/Fracture Lines	Nigerian Geological Survey (NGS)		2006

Spatial multi-criteria analysis (SMCA)

The SMCE method we used is described in the sub-sections below. A total of nine geomorphological, climatic and environmental factors were considered to generate the groundwater potential map for Nigeria; soil, elevation, slope, geology, lineament density (fault lines), temperature, rainfall, land cover, and surface water density.

Generating suitability factor maps

We reclassified all nine factor maps into groundwater suitability classes. First the rainfall raster layer (12 months sums) was summed to estimate the total rainfall across Nigeria. The map was then reclassified as follows; areas with high rainfall were considered to have more potential and the areas with lower rainfall were considered with less groundwater potential. The same operation was performed for the temperature raser, however, areas with higher temperatures were considered to have lesser potentials due to evapotranspiration and vice versa. For existing water bodies and fault lines, we generated raster density maps from drainage and fault lines vectors. Areas with high surface water and lineament densities are considered to have more potential, while areas with low water body and fault line densities were considered to have less groundwater productivity. The Shuttle Radar Topographic Mission (SRTM) data was used to extract elevation gradient across Nigeria. Lower elevations were considered to have more potential and vice versa. The slope in degrees was also generated from the SRTM data; areas on steep slopes were considered to have less groundwater potential, and areas on gentle slopes were considered to have more groundwater potential. The geology map of Nigeria consists of 86 comprehensive classes these were characterized into 10 suitability classes. The soil layer from Food Agriculture Organization (FAO) consists of about 172 detailed and 36 broad soil classes in Nigeria, these classes were categorized into 10 broad soil suitability classes for groundwater potential in Nigeria. The last factor is landcover, the European Space Agency (ESA) layer consists of 22 landcover classes in Nigeria, and it was also re-categorized into 10 broad landcover classes in consideration of groundwater suitability. For example, the paved surfaces (Built-up and Asphalt) and rock formations have minimal infiltration and were considered to have the least groundwater potential, and were exempted from the model. Vegetated areas and farmlands are considered to have more groundwater potentials, while water bodies (streams, ponds, lakes and rivers) are considered to have optimal groundwater potentials.

Standardization and overlay

The nine factors maps described above were standardized to a common scale of measurement. All maps were reclassified to an explicit ranking format (1–10 classes) to support assigning the significance and impact of each factor. This is to unify all units and classes of measurements across all factor maps into a standardized conformed unit (Ibrahim et al. 2020). These factor maps illustrate the suitability of a specified factor in a graduating scale, ranging from "not suitable and restrictions" (0), to "less suitable" (1–3), to "suitable" (4–6) and "highly suitable" (7–10). This implies that the higher the value, the more the groundwater potential. The multi-criteria analysis tool in ArcGIS verson 10.5 was used to overlay the nine factor maps. Firstly, all the factors were weighted according to their significance to groundwater potential, this is by assigning each a percentage of influence and summing influence to 100%. Furon and Lombard (1964) and Persits et al. (2002) have demonstrated the efficacy of using geology alone to model groundwater recharge globally. The aquifer capacity is dependent on the geological composition. As such, we assigned the highest percentage (25%) to the geological factor. While groundwater recharge is reported to be a component of rainfall-runoff (JICA 2014). As such, rainfall was the second most important factor we assigned (15%). Next, soil, surface water density, lineament density, landcover and elevation were assigned 10% each. Specifically, the significance of fracture zones to groundwater potential in Nigeria has been highlighted by several authors (Ajayi and Hassan 1990; Edet and Okereke 1997; Edet et al. 2011, 2012). Lastly, slope and temperature were assigned the lowest percentage of influence (5% each). An output value of the resultant maps (final suitability map) was produced using the 'weighted overlay' tool in ArcGIS 10.5. The value index of the final map shows a range from 1–10, indicating groundwater potential ranking in ascending order. First, we modelled the historic groundwater potential using all factor maps, however for the climatic factors, we used historic mean of summed rainfall and average temperature data from 1970 to 2020. Next, we simulated the futuristic groundwater potential for 20-year time windows (2021–2040, 2041–2060, 2061–2080, and 2081–2100) using the cmip6 temperature and rainfall projections. Note that the same enviromental factor maps were used for the futuristic model, under the assumption that landuses, surface water, lineaments, soil, geology, elevation and slope remained consistent.

Validation

Field data of groundwater measurements was obtained from the Surveying and Geo-informatics lab of the Modibbo Adama University of Technology Yola, Adamawa State. The data was generated from a survey of 24 boreholes in Adamawa State, Nigeria. The data consists of both hydraulic head and water quality data. The hydraulic data was rasterized and used for validation. The cell size of the validation points was aligned with our modeled data to enable easier comparativeness. Both field and modeled data were reclassified into 2 classes of high and low potential. For the modeled data, the 10 suitability classes were reclassified as follows; 1- 4 as areas with low potential, and 5–10 is areas high potential. While for the field observed hydraulic data; 0–10 was classified as areas with high potential, and 11–41 is areas with low potential. We achieved an overall accuracy of 87.5% (Table 2).

We also compared our groundwater potential map with BGS's (MacDonald et al 2012) African groundwater products and the UNESCO geological maps published in 1964 (Furon and Lombard 1964) as a way of further validation, since we could not access more field data for additional validations.

The summery of the factors, and broad processes described above are illustrated in Fig. 2 below.

Table 2 Evaluation of the accuracy of the groundwater potential model in Adamawa state

	Observed data		
	High to Low	High	Low
Modelled			
High to Low	21	–	–
High	0	2	0
Low	0	0	1
Total observation	24		
Accuracy	87.5%		

Results

Factor maps for ground waterpotentials in nigeria

The factor maps show an interesting distribution of distinctive ecological and climatic regions in Nigeria. As expected, the drainage density map shows more potential along the river Niger and Benue corridor, the southern parts of the country and the locations with a high concentration of existing dams, ponds and rivers in northern Nigeria are parts of Kano, Jigawa, Katsina, Gombe, Plateau and Sokoto state (Fig. 3A). We digitized about 2673 major, minor and mini lineament/fault lines in Nigeria and the density map shows more concentration in the northern parts of the country with more densities in Yobe, Gombe, Borno, and Zamfara States (Fig. 3B). This indicates more potential for groundwater penetration in these areas based on the lineament factor.

The relief map shows higher altitudes in; north central Nigeria especially Plateau, Bauchi and Kaduna States, Adamawa and Taraba States in the North East, Cross River and Ekiti states in southern Nigeria. While most parts of southern Nigeria are low-lands, which shows more groundwater potential based on the elevation factor (Fig. 4A). The slope in Nigeria is mostly gentle (0–7 degrees) and relatively gentle (7- 17 degrees) in most parts of the country except for the higher altitudes mentioned earlier with slope degrees from 17° to 41° and upto 41–85 in the few extremely high locations like the Jos Plateau, Taraba, Adamwa and Obudu in Akwa Ibom (Fig. 4B). The slope factor shows lower run-offs and good infiltration capability and subsequently groundwater recharge.

The 30 years mean annual rainfall map shows the southern part of Nigeria with high rainfall, this is expected, with rainfall recieved almost throughout the year, and thereby portraying more groundwater potentials. On the other hand, the northern part of the country receives lower rainfall (about 250 to 900 mm) throughout the year. This is with the exceptions of Adamawa, Taraba and Jos-Plateau highlands with annual rainfall from 1200 to 1800 mm recorded in these areas, as an effect of elevation (Fig. 5A). The same pattern

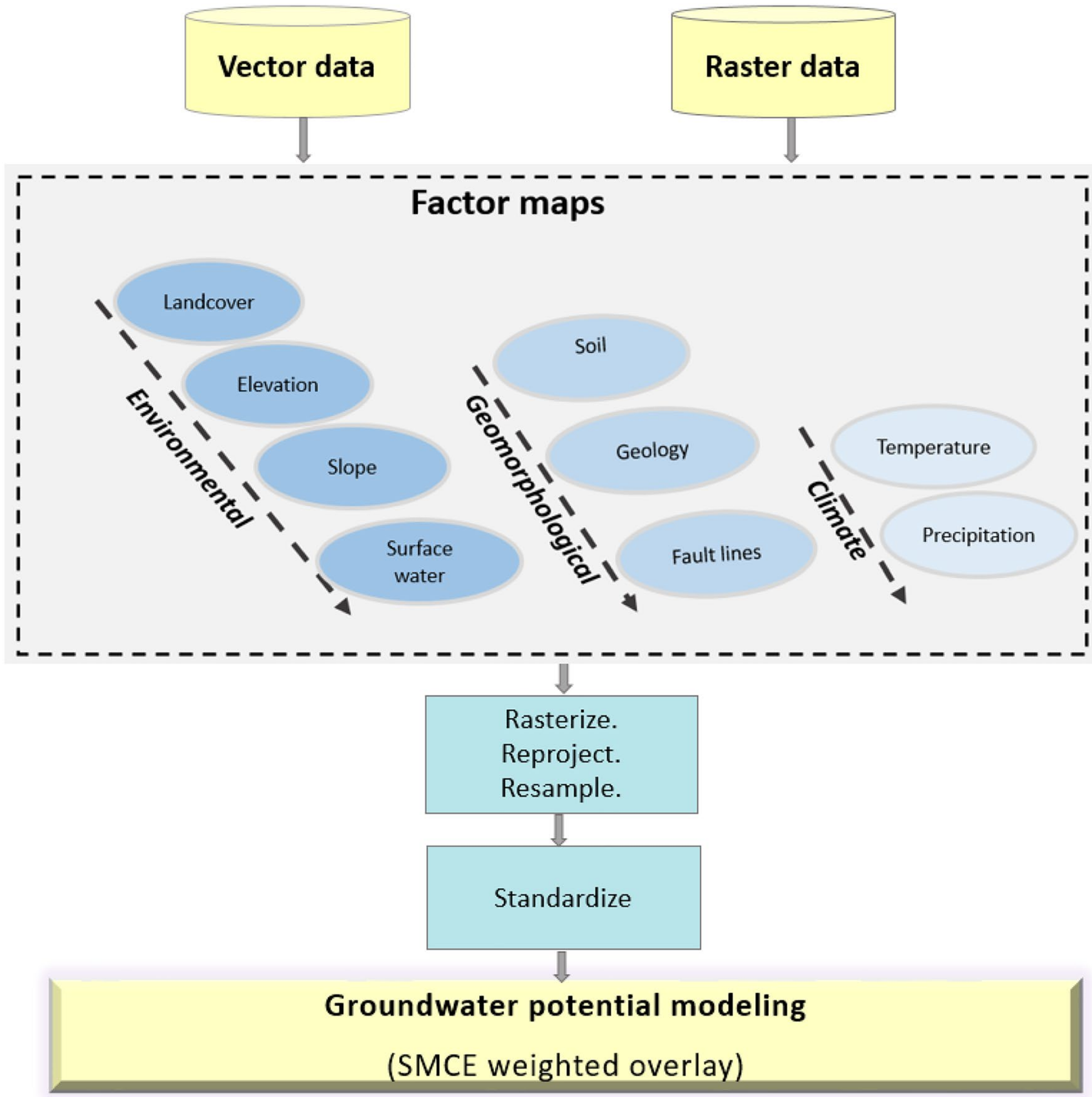

Fig. 2 Schematic Representation of the Methodological Flow Chart

is exhibited on the temperature map; higher annual mean temperatures of about 37^{0}C were recorded in the northern part of Nigeria, implying higher evaporation and lower groundwater potential and vice versa for southern Nigeria and upland locations.

The dominant geological compositions of north-central, parts of northeast and western Nigeria are the crystalline basement rocks, these are of metamorphic igneous-volcanic origin (Oyawoye 1970), and therefore, areas of lower groundwater potential due to these formations. This is vice versa for the southern Nigeria, with largely Precambrian crystalline basements (Fig. 6A). There are also numerous soil layers in Nigeria, but there are 36 broad classes. The most dominant class is luvisols, which consists of surface accumulation of humus overlying an extensively leached layer of soils and almost devoid of clay and iron-bearing minerals and are prevailing in western, north-central and northeastern Nigeria. Another dominant soil class in Nigeria is the fluvisols, which is located along the corridors of the major rivers. The predominant soils in upper northern Nigeria are Regosols and some areas Arenosols. These soils are poor in nutrients but very productive in groundwater recharge. Nitisols are the prevailing soils in the south-south, south-eastern and some parts of north central Nigeria, they also have a good groundwater potential (Fig. 6B).

The dominant landcover type in Nigeria were cultivated lands, covering up to 47% of the 923,763km^2 Nigerian landmass, these cultivated lands are concentrated in the northern parts of the country, and parts of the southwestern region (Fig. 10B). Farmlands are areas with good groundwater

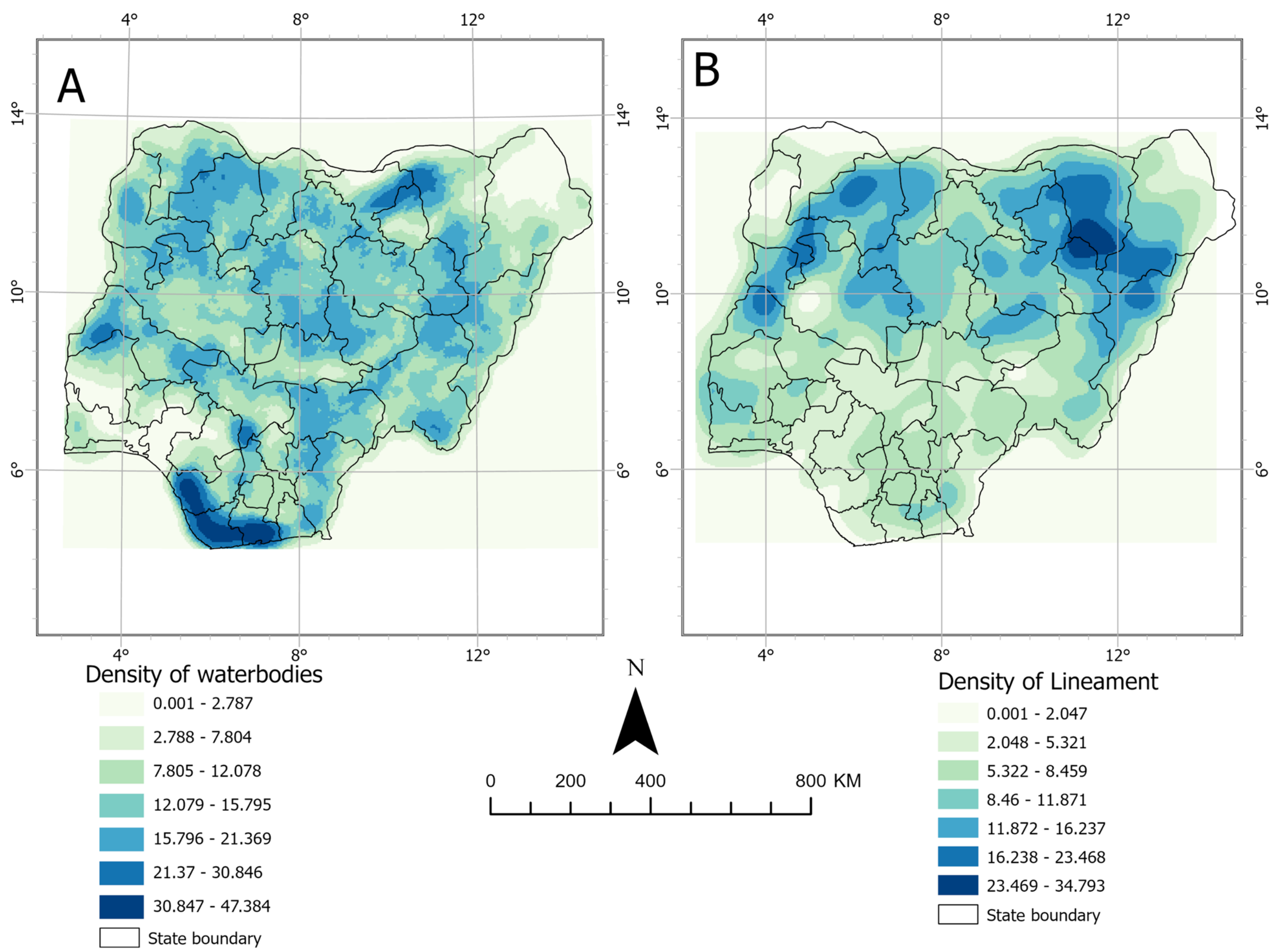

Fig. 3 Factor Maps Depicting, **A** Drainage Density map of Nigeria and **B** Lineament density map of Nigeria

potential due to tillage activities, and hereby paling these regions in good groundwater potential considering the landcover factor. The second principal landcover is 'other vegetation' (mainly comprising of woodland and shrubland) with 25%, then forested areas covering 19% of the Nigerian land area, and followed by natural grassland with 5%, these were also considered areas with good groundwater potential. The built areas (artificial surfaces), water bodies and rock formations cover only 4% of the total landmass (Fig. 8 B).

Groundwater potentials

The groundwater potential map presented in this study is a combination of all nine factors with a higher percentage of influence assigned to geology and lineament density in consideration of the aquifer, while rainfall, elevation, surface water bodies and soil are in consideration of the groundwater recharge. Our historic-present groundwater potential map shows an interesting pattern, revealing no location in Nigeria with optimal groundwater potential (9–10), or with very poor or no groundwater potential (1–2). The suitability map shows a potential value ranging from 3 to 8 (Fig. 7). The values in the suitability map were translated to potential productivity classes from very low (3) to very high (8) as shown in Fig. 7B. Areas under very low groundwater potential cover about 188,44 km^2, these are dominantly on rock formations, while about 246,939 km^2 falls within the areas with low potentials, largely of the basement complex. The areas with moderate potential are the largest category with about 44%. Areas with high groundwater potential are largely within the major river corridors in the North and the Southern parts of Nigeria, covering up 129,303km^2. The areas identified with very high groundwater potential in Nigeria have the least coverage, with a total area of 160,37 km^2 and covering only 2.2% of the total landmass. This falls largely at the coastal areas in the south, with patches in Adamawa, Gombe, Kebbi and Niger states.

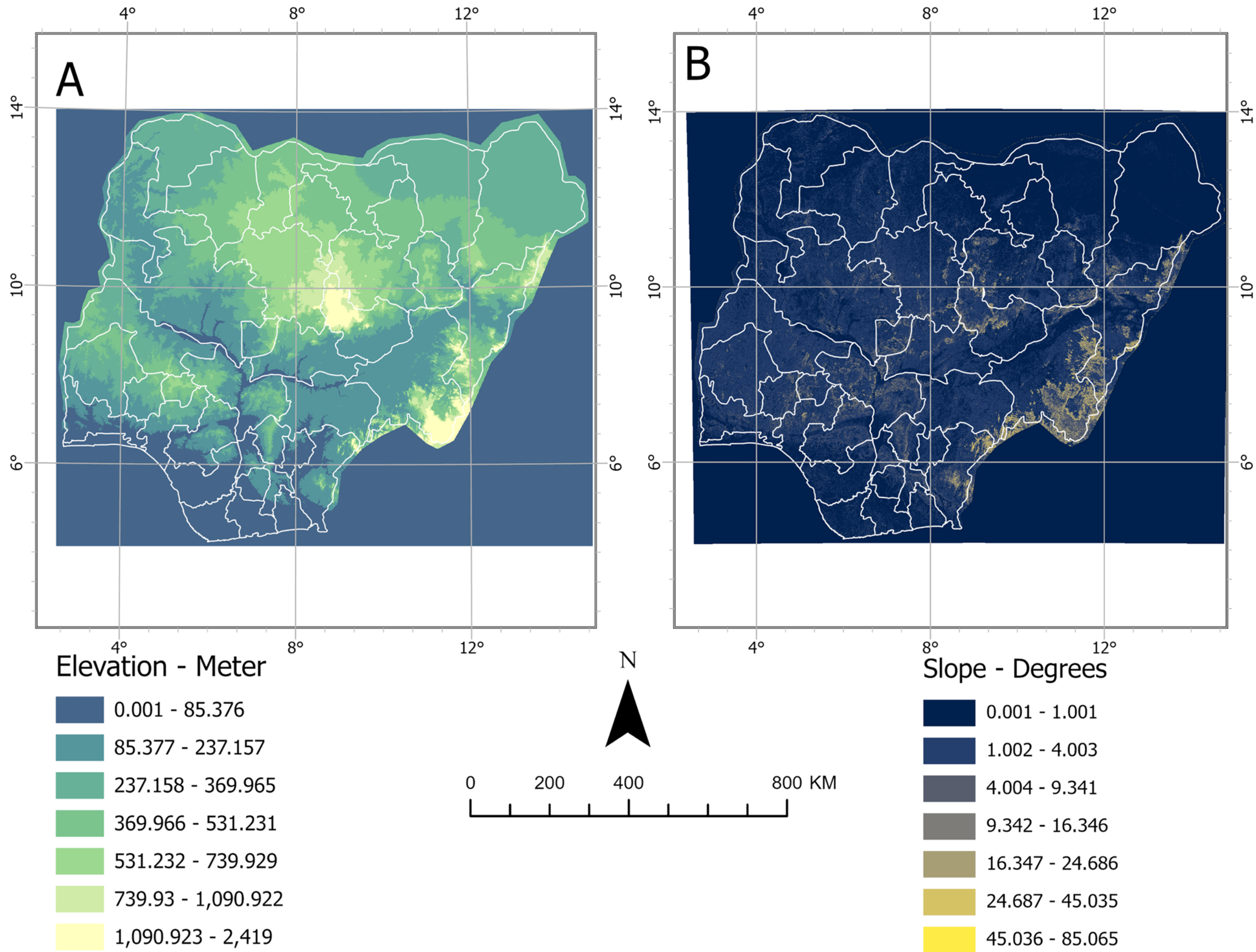

Fig. 4 Factor Maps illustrating, **A** Elevation map of Nigeria and **B** Slope map of Nigeria

Water potentials and supply challenges in Nigeria

We compared the settlement density map, landcover, surface water and groundwater potentials to spatially highlight concentration areas for water demand, and potential areas of deficits. Both surface water and groundwater are densely clustered along the same regions, revealing a deficit in other parts of Nigeria (Fig. 8C, D). The surface and ground water maps show higher water availability in areas with dense settlement concentration (Fig. 8). While the farmlands are concentrated in the Northern parts, where there are lesser natural rivers and streams. This explains the high concentration of irrigation dams in these areas, as well as boreholes for irrigation purposes, especially in Kano State.

The groundwater (Fig. 8C) and surface (Fig. 8D) maps show a close relationship between areas with very high-groundwater potential and areas containing surface water. Surface water covers about 19,202 km^2, which is about 2.1% of total Nigeria's landmass. The natural water bodies (Ocean, River, Lake) have about 79.7% of that area, irrigation projects cover 5.3%, while reservoirs and ponds cover about 15% of the total water bodies (estimated from Nigeria's surface water map). There are also small seasonal streams that were not included in the analysis. but also significant water sources in Nigeria used for both domestic and irrigation purposes. These natural and artificial water bodies are scattered across Nigeria including two major rivers (Niger and Benue), although the concentration of natural water bodies is in the southern parts of Nigeria as an impact of elevation and the ocean (Fig. 8D). While irrigation and hydroelectric dams are concentrated in the northern parts of the country as well as a few natural streams and rivers.

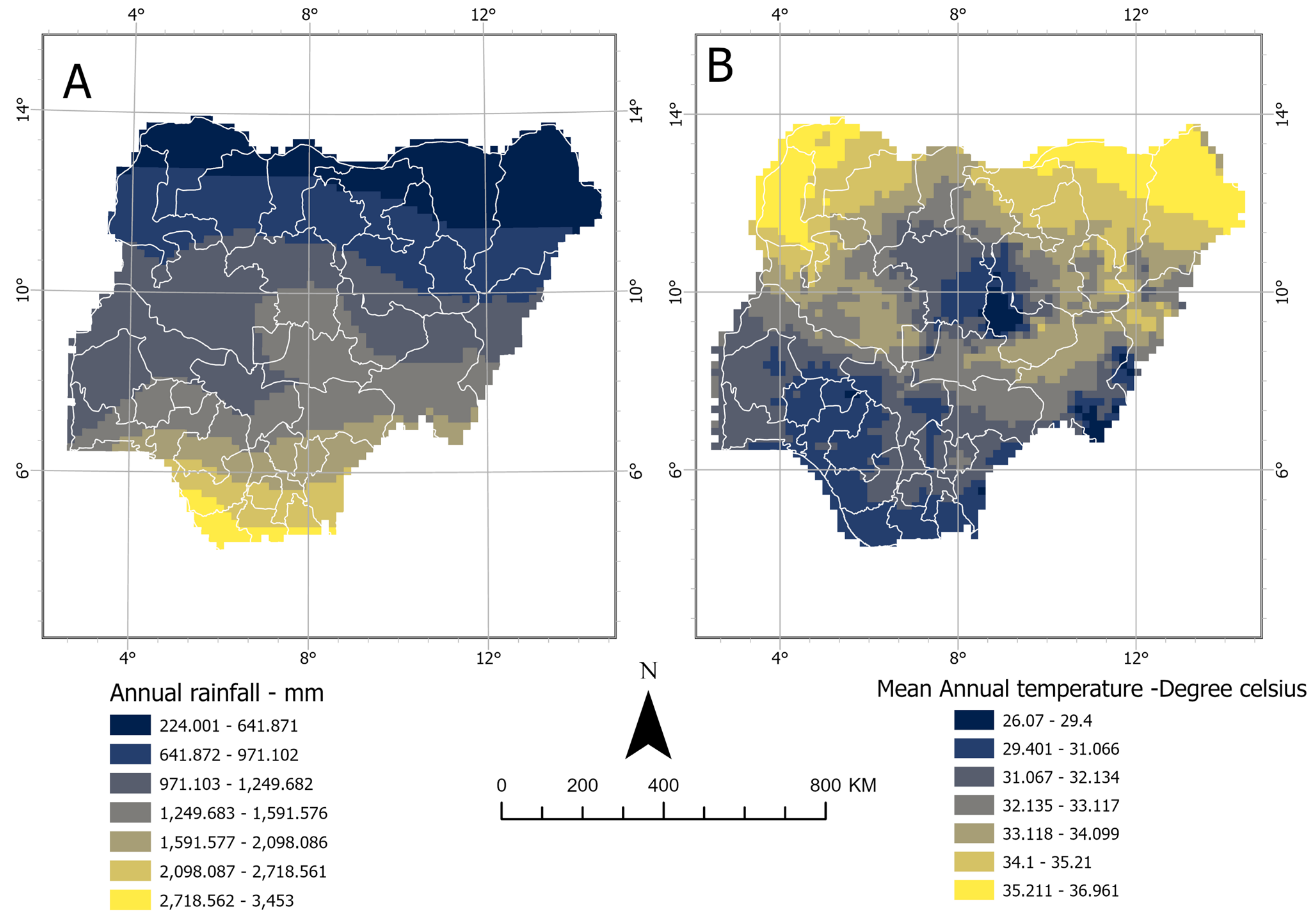

Fig. 5 Factor Maps showcasing, **A** Mean rainfall map of Nigeria 1970–2020 and **B** Mean temperature map of Nigeria from 1970 to 2020

Validation of groundwater potential

We have validated the potential map using the recommended field groundwater data and our results achieved up to 87.5% in the Adamawa region (Table 2). Our map is comparable with the BSG's ground water and the Federal Ministry of Water Resources (FMWR) and United States Agency for International Development (USAID) map products (Figs. 9 and 10). Our groundwater map is almost a replica of the BSG's groundwater productivity and groundwater storage maps, and our map is on a finer spatial scale. Although, MacDonald et al. (2012) have brought to focus that groundwater estimations work very well in areas of low relief, but performed very poorly in areas of high relief especially on a large scale.

Groundwater future potentials

Our projection results show a persistent increase in groundwater potentials from 2021 to 2100 (Fig. 11), this can be attributed to the cumulative projected increase in rainfall over most parts of Nigeria. A significant change in groundwater is revealed where the majority of the 'low-medium potential' was projected to transit to 'Medium–high' from 2021 to 2100. Likewise, the areas under 'very high' potentials were projected to increase especially in the southern and major riverine areas of Nigeria. Our projections show that areas with very low and low groundwater potential are likely to drastically reduce or disappear by the end of the century.

Discussion

JICA (2014) highlighted that the amount of groundwater development is dependent on both groundwater potential and aquifer capacity. Rijswijk (1981) set the background for groundwater estimations in Nigeria, however, this estimates are old and did not account for environmental factors. Although recent research work from BGS (2011) and JICA (2014) provided more recent estimates. However, there is need for continuous evaluations, with more precise and up-to-date estimations due to increasing population, environmental degradation and climate change using simple but

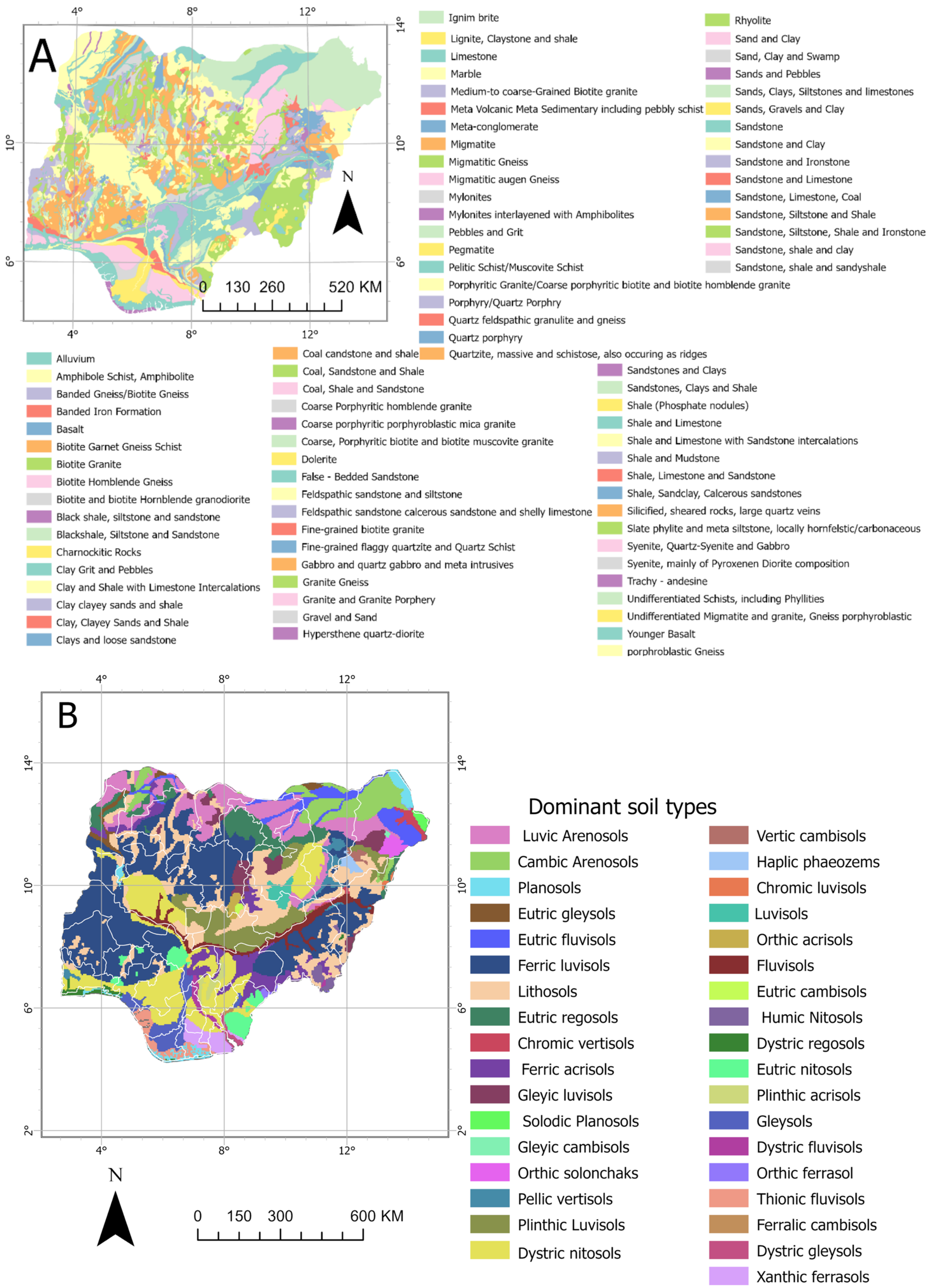

Fig. 6 Factor Maps presenting, **A** Geology map of Nigeria and **B** Soil map of Nigeria

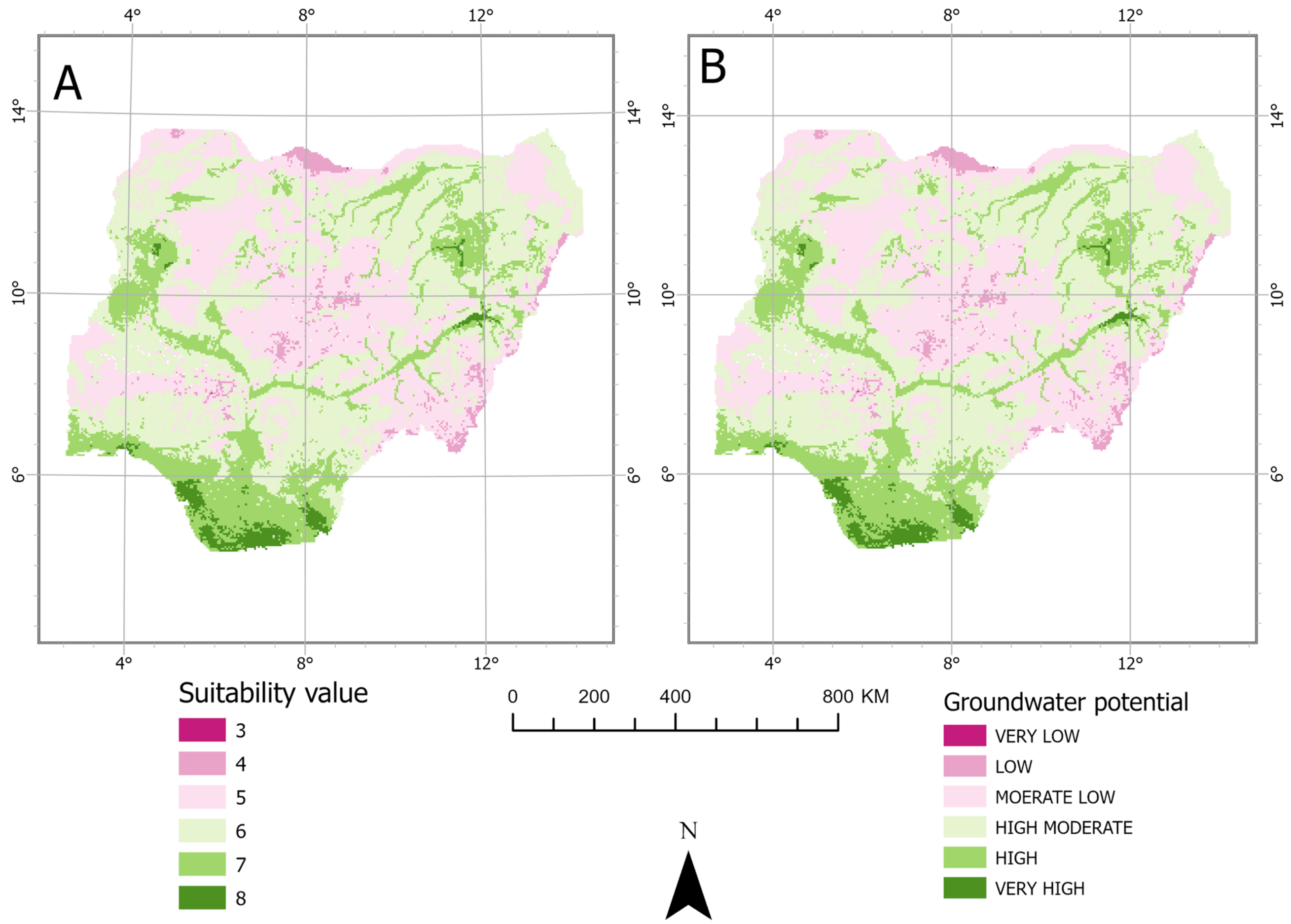

Fig. 7 **A** Map displaying Groundwater Potential Values and **B** Classified Groundwater Potential Map of Nigeria

robust data and tools. As such, we modeled historic-present and futuristic groundwater potentials for Nigeria considering nine geological, climatic and environmental factors.

Factor maps for ground water potentials in Nigeria

Our results revealed different potentials for all the nine factors in the regions of Nigeria. The rainfall and temperature factors revealed that the northern part of Nigeria is disadvantaged with lower rainfall and higher temperatures, while the opposite is revealed for southern Nigeria and upland locations. Conversely, the northern part of the country with gentler slopes and higher fault-lines densities encompasses greater potentials in terms of groundwater recharge compared to the southern region. In terms of elevation, the southern parts have more groundwater potentials. The geological map of Nigeria shows diverse geological classes but can be categorized into two main lithological units, the precambrian crystalline basement and cretaceous-tertiary sedimentary rocks (Edet et al. 2011). The latter being dominant in most parts of the northern Nigeria, thereby representing a lower potential in terms of ground water potential. While the sedimentary basins are broadly divided into basal non-marine sandstones, siltstones, and mudstones (Petters 1982), and they have more groundwater potentials. In terms of the soil factor, most parts of Nigeria are suitable for groundwater recharge. The prevalence of luvisols in western, north-central, and northeastern Nigeria can be linked to high groundwater potentials in these locations, as luvisols are more suitable for groundwater recharge compared to other soil classes. Luvisols, sometimes referred to as lateritic soils, have properties that allow groundwater recharge in tropical and subtropical areas (Junge & Skowronek 2007). High porosity, moderate to high permeability, a lateritic horizon rich in iron and aluminum oxides, a balanced chemical composition, different clay contents, and a topography that promotes water movement are some of these characteristics. The combination of these elements, as well as the impact of native flora, makes luvisols more successful in encouraging water to seep into the earth and sustaining groundwater recharge (Bargués Tobella 2016; Junge and

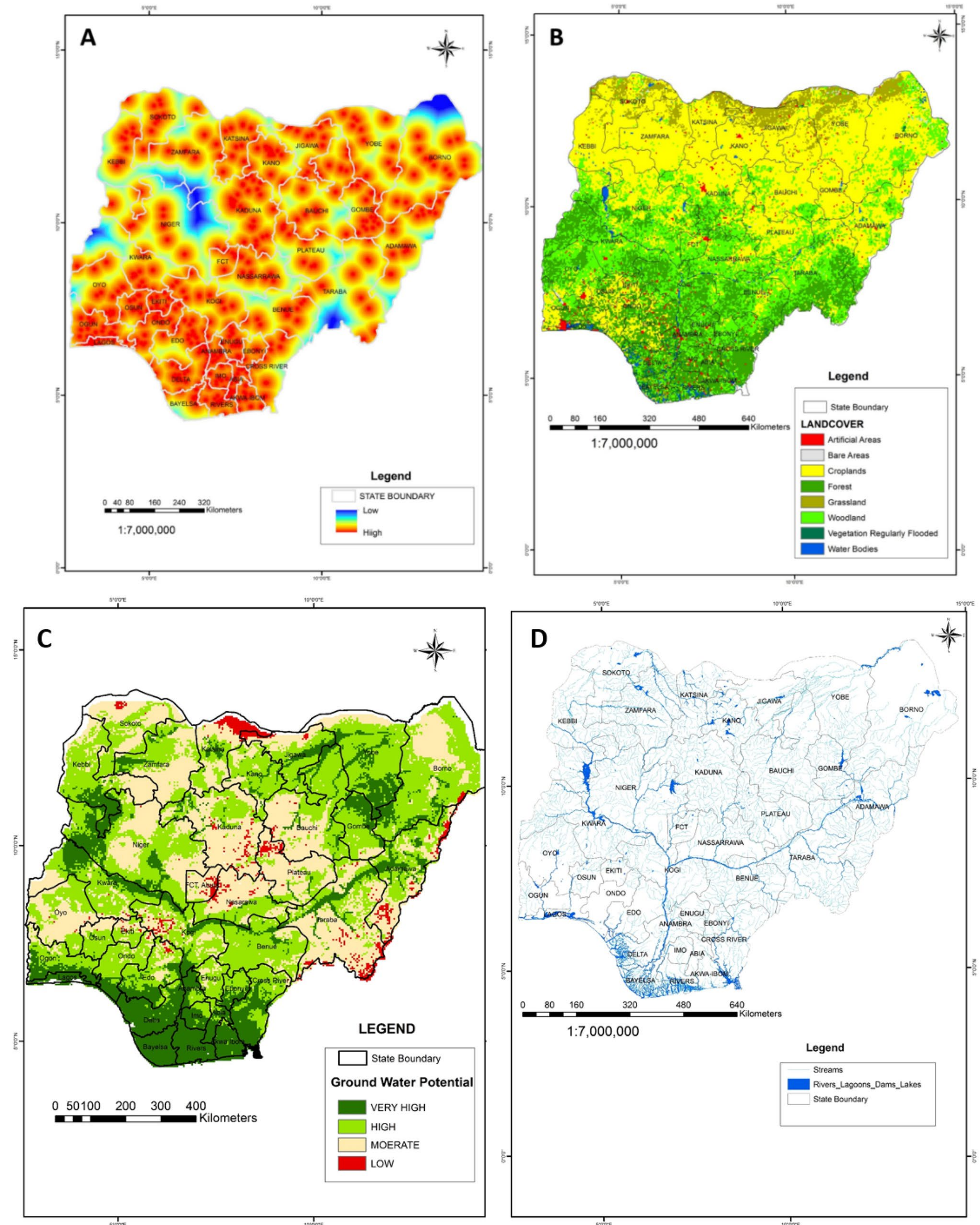

Fig. 8 **A** Map depicting Settlement Density in Nigeria, **B** Landcover Map of Nigeria, **C** Groundwater Potential Map, and **D** Surface Water Map of Nigeria

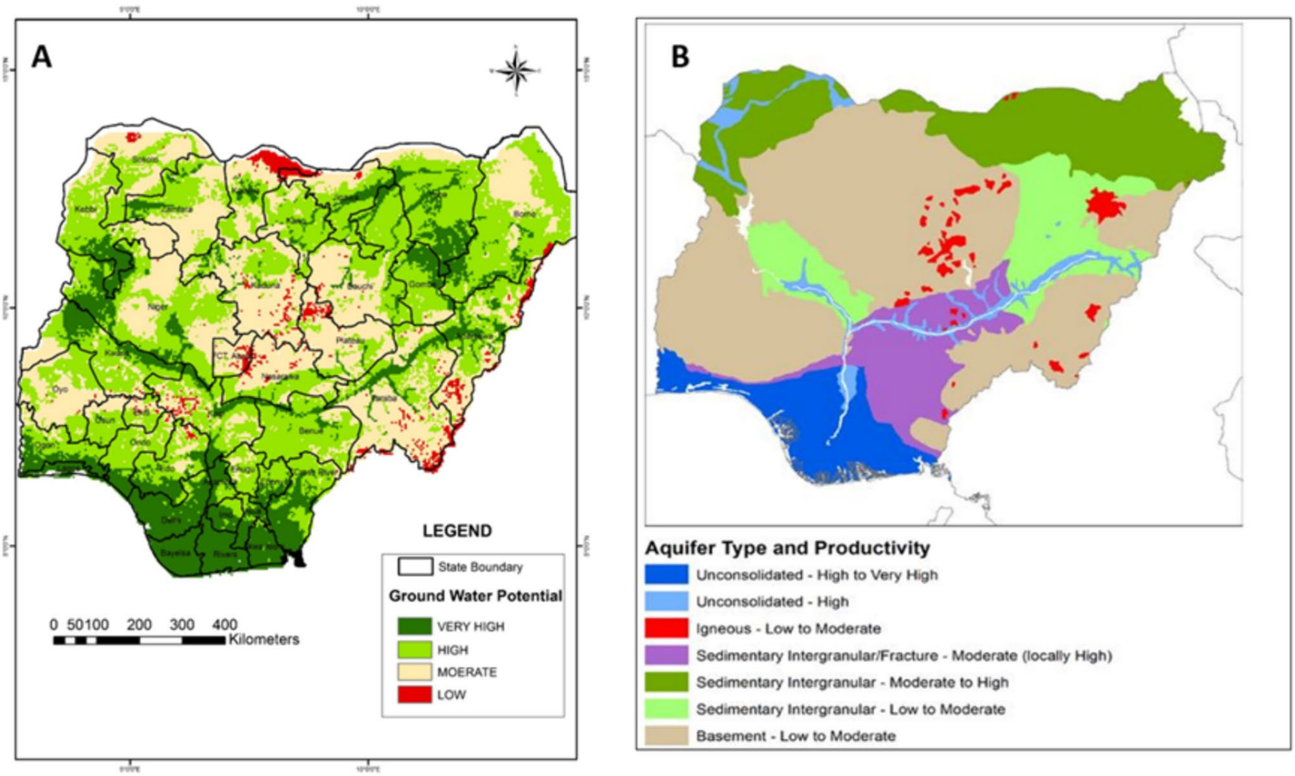

Fig. 9 **A** Groundwater Potential Map by Ibrahim et al. (2024), and **B** Hydrogeological Map of Nigeria (Source: FMWR, 2000; USAID 2010)

Skowronek 2007). Ultimately, all nine factors explain our final groundwater potential map.

Groundwater potentials

Our groundwater map indicates that no location in Nigeria has optimal groundwater potential (9–10) or very poor potential (1–2). This also corresponds with the African groundwater productivity and storage maps by MacDonald et al. (2012). Ultimately, the movement of groundwater is significantly affected by geology, for example, groundwater moving in weathered basement rock can flow into a river latest within one month after rainfall, while groundwater that flows within sedimentary rock takes several months to flow into the river but dependent on the hydrological structure of aquifer (JICA 2014). Note that, geological structures alone have been used in predicting the aquifer potential and productivity of groundwater (Fig. 9B). For example, the African groundwater hydrogeology Atlas at a scale of 1:5 million for Africa by Persits et al. (2002) was based on UNESCO geological maps published in 1964 (Furon and Lombard 1964). Our groundwater map in comparison to this product displays a similar pattern despite the infusion of several other factors (Fig. 9B). This further demonstrates that the relationship of human activities in a given environment is influenced by climate, ecological and geomorphic factors (Fig. 10). It also highlights the suitability of our method for frequent and near-real time groundwater monitoring especially under climate change and unregulated groundwater harvest in Nigeria.

Water potentials and supply challenges in Nigeria

Figure 8 revealed different distributions of ground and surface water. It also further compares with landcover and settlement densities, and spatially elucidates concentration areas for water demand and potential areas of deficits. With increasing population trends in Nigeria, water supply is not met in both rural, semi-urban and urban areas. As well as critical shortages recorded for irrigation (Ibrahim et al. 2020), as most of the water sources used for irrigation are seasonal streams. The streams dry up before the onset of rain, crops wilt and dies before the optimal harvests are met, leading to extensive reports of yield losses (Ibrahim et al. 2020). The development of water resources in Nigeria has not risen alongside with population and agricultural increases. With fewer commitments in budgetary allocations for water projects, the Nigerian government has relied heavily on international interventions concerning water supply for its citizens. Even disturbing is future water demands

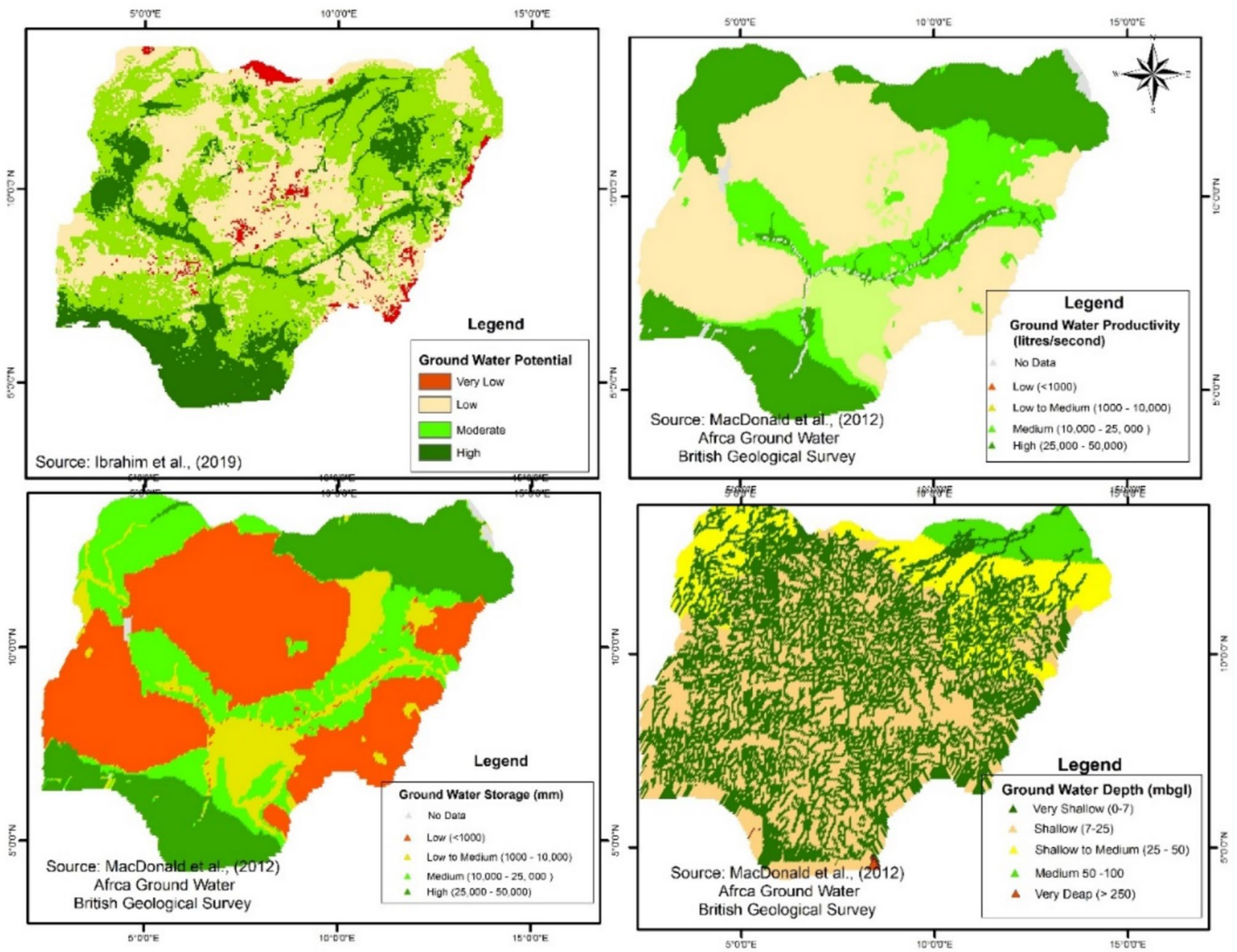

Fig. 10 **A** Map of Groundwater Potential in Nigeria by Ibrahim et al. (2024), **B** map of Groundwater Productivity in Nigeria, **C** map of Groundwater Storage in Nigeria, and **D** map of Groundwater Depth in Nigeria

which are projected to reach 16.58 BCM/year by 2030 (JICA 2014). The potential projected sources are surface and groundwater, even though about 34% of the Nigerian population obtain water for domestic uses from unsafe surface water bodies (Omole 2013). There are even more acute water shortages in the Northern parts of Nigeria, which is recording accelerated desertification (Ibrahim et al. 2022).

There is an abundance of surface water in Nigeria (Fig. 8) and largely harnessed for irrigation purposes. However, groundwater is the most widely used water chain for domestic use in Nigeria (Omole 2013), because of availability and it is extracted close to the point of need (MacDonald et al. 2009). This is why boreholes and wells have continued to spring up in Nigeria at an alarming rate since then, every landowner with the finances to sink a well or borehole have done so. This is because the responsible state and federal government agencies have failed to meet up the ever-increasing water demands in Nigeria. These have heightened uncontrolled exploitation of groundwater, which can lead to environmental problems (Ministry of Water Resources 2013). Solar pumps are becoming more popular recently. Southern Nigeria employs deeper boreholes, while the north depends on shallow aquifers and have more wells (Omole 2013). The three main issues are overexploitation, quality, and climate change. Integrated management, community engagement, and adoption of new technology for centralized generation and distributions of groundwater are key components of the future. There is little or no attention afforded to the issues of the regulation of water drilling activities in cities and villages. In Abuja alone, with an area of 1769 km^2, about 110,000 boreholes have been drilled and more than 330 metric tonnes of groundwater are harvested daily (Mekwunye 2013). Some of these areas are new discharge points for basement aquifer with limited water recharge, leading to high depletion of shallow aquifers especially those within the overburden or weathered layer of the basement complex.

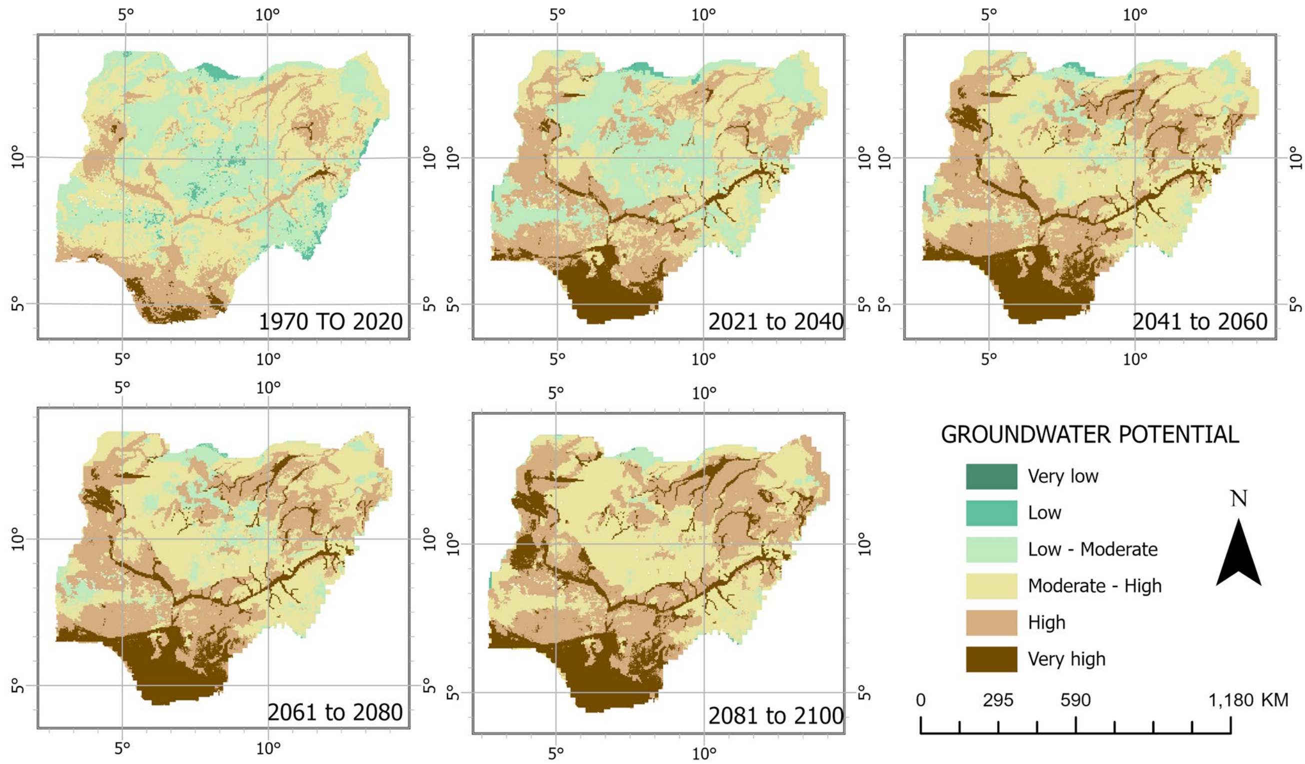

Fig. 11 Groundwater projection 2021 to 2100

From the year 2011 to 2018, it was reported that the average depth of borehole in Abuja has increased from 40 to 80 m (Mekwunye 2013). This further establishes concerns that, despite the potential in groundwater in Nigeria aquifer is becoming deeper due to increased groundwater harvest. This has begun to cause major vacuum underground and some recent earth tremors in Abuja, Kaduna, and Oyo, where it is attributed to excessive borehole drilling especially in Abuja, the nation's capital city (NASRDA 2018). Likewise, the quantity and quality of groundwater have changed over time, specifically fossil aquifers which are known as non-renewable underground water reservoirs due to their very slow rate of recharge (Margat et al. 2006). These can further exacerbate current water challenges, especially under climate change. The vision 2020 water supply goal is set to meet 100% of water demand in Nigeria by 2030. Though, the future projections show a groundwater pumping of 2.6 BCM/year from newly drilled boreholes and 1.0 BCM/year by rehabilitated boreholes to meet this target. The plan is for 16,000 boreholes with motorized pumps for urban/semi-urban/small-town water supply. About 10,000 motorized boreholes are projected for rural water supply, supplemented by 83,000 boreholes hand pump boreholes (JICA 2014). With the current situation of deeper aquifers, these projections further highlight impending environmental problems. Included in the discussions pertaining to changing water quality due to pollution especially in Niger Delta (UNEP 2011), dissolution of evaporate minerals in the Benue Basin (Ekwere and Ukpong 1994; Tijani 2008), problems of acid mine drainage in areas around coal mines in Enugu were reported (Nganje et al. 2011), and septic polutions (Daffi et al. 2020). These issues highlighted here are concerns enough to seek centralized and sustainable water chains in Nigeria.

Groundwater potentials, depths, productivity, storage and climate change in Nigeria

The BGS's African groundwater assessments were calibrated and validated with national and regional hydrogeological maps, geological units and peer review journals. They have however emphasized the need to validate African maps with observed groundwater-level data to enhance the quality of hydrogeological data in Africa, which we have compared with our groundwater potential map. Focusing on the Nigerian extend of the African groundwater depth map, there is good groundwater potential in Nigeria mostly at very shallow, shallow and moderate depths. Mostly at depth levels less than 50 m which can be easily accessed by a hand-dug well and hand pump boreholes (BGS 2011). The Nigerian citizens are well aware of this potential and explains the number of hand wells and boreholes in the country. However, there is a need for an evaluation to balance groundwater use and recharge (Eman et al. 2018). Christopher et al. (2003) have also discussed groundwater levels and depths in Nigeria specifically and highlighted different yields at different hydrogeological units and results are similar to the BGS estimates. In Gwandu aquifer 10–35 L/s, in the Kerri Kerri aquifer it has a yield of 1.25–9.5 L/s, the Chad Basin with three main aquifers; 2.5–30 L/s, the upper aquifer, 24–32 L/s for a middle aquifer and 10–35 L/s for the lower aquifer, and so on. Although there are issues of drought causing lower groundwater levels, both in dry seasons and when lower rainfall is recorded during the rainy season, especially in basement aquifers (Ministry of Water Resources 2013). These issues have thereby brought to attention the uncertainties of groundwater potential in Nigeria under climate change, combined with the accelerated water demands and groundwater contamination (Ekwere and Ukpong 1994; Tijani 2008; Nganje et al. 2011; UNEP 2011; Daffi et al. 2020).

There are growing concerns about the uncertainty of how climate changes may further affect groundwater in Nigeria. Even though discussions are that groundwater responds much slowly to meteorological conditions than surface water and is perceived as a natural buffer against climate variability (Calow et al. 2010). Still, there is a need to seek caution in the pattern of un-regulated and incessant groundwater harvest in Nigeria. Two threats to Nigeria's groundwater resources are uncontrolled pumping and climate change. It might be catastrophic to ignore how the climate including temperature, rainfall, and other factors affects this priceless resource (George-Ukpong 2012). Our results revealed that some of areas with low to moderate ground water potential corresponds with areas already experiencing severe climate change consequences especially drought. This can only further exasperate the ground water recharge if incessant hand-dug wells and boreholes drilling continues. Also, rising sea levels put coastal areas at risk of saltwater intrusion as well as the levels of groundwater may be dropping in densely populated urban areas that are developing quickly (Fagbohun 2018). JICA (2014) has simulated the long-term rainfall-runoff simulation model to estimate the effect of the change in precipitation and air temperature on runoff and subsequently groundwater recharge and results show that groundwater recharge is decreased with 14% to 20% due to climate change effects in Nigeria. Although they suggested that the amount of reduction in groundwater recharge is different in different locations, areas with slower groundwater recharge will have a larger influence compared to areas with higher groundwater recharge. Their results further reveal that the northern part of Niger and Chad Basin will have lower impacts on the decreased groundwater recharge compared to other areas and decreased groundwater level will be catastrophic in areas far from water bodies. This is consistent with our projections in Fig. 11, but contrary to reports by Mekwunye (2013), who indicated that Nigeria's high-potential groundwater zones are depleting. However, he attributed this to a combination of shifting land use and climate change in the highly populated and fast growing Abuja area. The main factors that will exacerbate this are lower precipitation, higher temperatures, and erratic weather patterns. In addition, land use changes like deforestation, settlement expansion, and unsustainable farming methods, leaving less water for aquifers to absorb. However, our groundwater projection revealed a persistent increase in groundwater in all the time stamps projected until the end of the century (2100). This can be attributed to the projected increase in both temperature and rainfall in the region until 2100 in Nigeria based on the cmip6 data used in modelling future groundwater potentials and under the assumption that landuses remains consistent environmental and landcover maps were used throughout the projections. The projected increase in rainfall in the cmip6 raster, far outweighs the temperature increase projected for Nigeria, this somehow balances the groundwater potential and recharge in our model. Notwithstanding, with population increase and growing water demands associated, the technologies, cost and energy required to harvest groundwater in Nigeria may change due to deeper aquifers. To ensure a resilient water supply in the future and to adjust to changing climatic circumstances, integrated water resources management that takes into account the interconnections between surface water and groundwater is essential. It is essential to incorporate climatic data into monitoring programs. This makes it possible for laws to be well-informed, better extraction rate management, and early warning of droughts or depletion. This integration can be made feasible with the help of tools like modeling, remote sensing, and community involvement. In the end, Nigeria's groundwater future depends on adopting climate-aware strategies. Cooperation between governmental organizations, environmental agencies, and research institutions is crucial to guaranteeing a sustainable supply of water to manage these potential (Danielopol et al. 2003). Data sharing, collaborative research and monitoring projects, policy creation, capacity building, infrastructure planning, frequent consultation, and disaster response planning are some of the major endeavors. In order to manage water resources holistically and sustainably, this cooperative strategy attempts to incorporate scientific research, well-informed legislation, and efficient management techniques.

Conclusions

With the rising increase of groundwater harvest in urban and rural areas in Nigeria, there is a need for continuous groundwater modelling using geological, climatic and environmental data and spatial tools. The groundwater factors show an interesting pattern across Nigeria, where the southern parts show more potential of surface water density, rainfall, temperature, soil, land cover and elevation are considered. Likewise, the upland locations with higher rainfall and lower temperatures indicate suitable places for groundwater recharge but are disadvantaged by geomorphologic factors. On the other hand, northern Nigeria shows more potential considering geology, soil, lineament density and slope, but disadvantaged by climatic factors. The main focus should be monitoring groundwater. Factors like geological composition and soil are static but climatic factors and landcover are changing. Our groundwater map implied areas of concern due to climatic and environmental changes, especially locations away from surface water buffers can be affected with a decrease in rainfall. Our projected maps shows increasing groundwater potentials until the end of the century (2100). There is need to seek caution considering recent extensive groundwater extractions and changing landcover systems, especially in urban landscapes. In another vein, the excessive groundwater extractions are linked major vacuum underground and some recent earth tremors in Abuja, Kaduna, and Oyo. Coupled with the current reports that groundwater aquifer is deepening in Nigeria, future water projections further highlight impending environmental problems, especially under climate change. The three main issues are overexploitation, quality, and climate change. Consolidated water management, community engagement, and adoption of new technology for immediate centralized water production and supply are key components of the future to enhance sustainability and curb water challenges in Nigeria.

Nigerian groundwater distribution is influenced by geological, meteorological, and environmental variables. The many geological formations in the nation, including crystalline rocks and sedimentary basins, have an impact on the presence and flow of groundwater. Using environmental remote sensing data shows more factors that translates to low or high groundwater potentials. For example, the factor maps show the influence of surface water, landcover and elevation to groundwater potentials. Likewise the unique rainfall distributions and seasons are essential for groundwater replenishment, as such areas with high rainfall show higher groundwater potentials. Therefore results from GIS analysis highlight that the availability and quality of groundwater are also impacted by changes in land use, urbanization, and agricultural practices. Our findings can guide local and national allocations, and the implementations of national and international programs for informed water policies and pragmatic solutions towards sustainable water monitoring and management in Nigeria. Regular updates, approximately every three to five years, or near-real time monitoring of groundwater potential using geospatial tools are recommended. This frequency ensures the relevance and accuracy of the assessment by accounting for environmental and climate changes, data quality improvement, policy adaptation, population growth, technological advancements, and risk mitigation. The benefits include providing policymakers with current information for informed decision-making, addressing emerging issues, and engaging with communities. Periodic updates contribute to sustainable groundwater management and the development of effective government policies. For future studies, we recommend the assessments of climate change effects in addition to examining land-use changes, incorporating cutting-edge remote sensing technologies, improving hydrogeological models, evaluating groundwater quality, taking into account social factors and community involvement, investigating the interactions between groundwater and surface water, creating groundwater vulnerability maps, utilizing big data and machine learning, performing temporal analyses, involving stakeholders in the development of policy, and improving groundwater monitoring networks amongst many areas of improvement.

Lastly, despite the potentials in groundwater across Nigeria, the true amount of currently available groundwater (storage and depth) needs to be further validated across the Country. This could not be achieved due to lacking datasets; the accuracy of our map is achieved for a small part of Nigeria. We hereby recommend further validation using ground data from different regions of the country.

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Data Availability We offer free access to our groundwater potential map (raster and vector) for validation and other research use. Please contact the corresponding author for access.

Declarations

Conflict of interest The authors declare no conflict of interest.

Informed consent statement We have referenced the sources of all external maps and data according.

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