



Overview of the application of geospatial technology to groundwater potential mapping in Nigeria

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Abstract

Sustainable development of groundwater resources in many developing nations like Nigeria is hampered by paucity of information about the resource. Geospatial technology has provided useful information in understanding the distribution of groundwater throughout the world for the purpose of planning, exploration, monitoring and conservation. Numerous studies have integrated remote sensing (RS) and geographical information system (GIS) in the assessment of groundwater potential in different parts of Nigeria. This paper therefore aims to review the literatures and reveal the successes and most importantly the challenges faced by such studies and provide useful recommendations for improvement in future research. A global perspective of advances in the application of geospatial technology to groundwater mapping was first captured from where the strength and weaknesses of the same application in Nigeria in terms of methodology of data extraction, modelling and validation were assessed. The review shows that less than 20 bibliographies are available with about 50% from the south-western part of the country. Few parameters controlling groundwater are often analysed and categorised without any standard. Most models are produced from software packages that do not allow weighting of thematic layers hence cannot incorporate expert judgements. Areas needing urgent attention for improvement include: time of remote sensing data acquisition, methods of parameter extractions, standard GIS software packages used, novel models and comparison between models and the need for model and map validations. Recommendations on country wide coverage of groundwater potential assessment, provision of groundwater monitoring facilities and strict adherence to groundwater development standards were also made.

Keywords GIS · Groundwater · Mapping · Nigeria · Remote sensing · Review

Introduction

The paucity of information on water resources especially in developing countries like Nigeria is one of the major obstacles to sustainable development of the resource. Water is a valuable resource that supports life, ecological diversity and economic development. Its scarcity is a major cause of poverty, hunger, diseases and a significant contributory factor to humanitarian crises (EL-Baz 2008). To saturate the information

gap on water resources, Earth observation technologies together with observation of water cycle have been in the past few decades employed to provide reliable and timely water information. Water resources can broadly be divided into surface and groundwater. Surface water (e.g. streams, rivers and lakes) availability is no longer promising. Where available, its quality is threatened by human activities; thus, seeking alternative source in groundwater becomes expedient. Groundwater development is relatively cheaper, takes a shorter time to develop once favourable spots are located, is less susceptible to pollution than surface water sources and has widespread availability (Jha and Chowdary 2007; Talabi and Tijani 2011; Ahmed II et al. 2013).

Several conventional methods exist for the exploration of groundwater which are mainly based on ground surveys (Ganapuram et al. 2009). These methods include geological, geophysical, hydrogeological surveys and drilling (Prasad et al. 2007; Talabi and Tijani 2011) which are considered

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expensive, time consuming and difficult to carryout in rugged and inaccessible terrains (Bala et al. 1999; Jaiswal et al. 2003) and may not be highly reliable due to assessment of only a few factors that affect the presence of groundwater (Jaiswal et al. 2003). However, the advent of geospatial technology has now provided a cost effective and timely means of groundwater exploration which is applicable even in inaccessible areas (Pradhan 2009; Manap et al. 2013; Nampak et al. 2014). Remote sensing and GIS have become important tools in the field of hydrogeology for assessing, monitoring and conservation of groundwater resources (Prasad et al. 2007; Jasrotia et al. 2012). The National Remote Sensing Agency of India was the first to integrate information from remote sensing and GIS to delineate groundwater recharge potential zones in 1987 (Yeh et al., 2009). Since then, many studies have utilised geospatial technologies to groundwater investigations with impressive results (e.g. Edet et al. 1996; Solomon and Quiel 2005; Hammouri et al. 2012; Razandi et al. 2015). Furthermore, Jha et al. (2007) grouped the application of remote sensing and GIS in hydrogeology into six categories namely, exploration and assessment of groundwater resources, selection of artificial recharge sites, subsurface flow and pollution modelling, groundwater pollution hazard assessment and protection planning, estimation of natural recharge distribution and hydrogeologic data analysis and process monitoring.

Numerous statistical methods/models have gradually been employed with spatial and thematic data in producing groundwater potential zonation and recharge maps. These models can generally be grouped into three: *GIS base models* using Weighted Index Overlay and Combinations (e.g. Musa et al. 2000; Shaban et al., 2005; Adji and Sejati 2014; Senthil Kumar and Shankar 2014). *Probabilistic models* using multi-criteria decision analysis (e.g. Fenta et al. 2014; Rahmati et al. 2014), frequency ratio model (e.g. Oh et al. 2011; Razandi et al. 2015; Guru et al. 2017), logistic regression model (e.g. Ozdemir 2011; Pourtaghi and Pourghasemi 2014), Dempster Shafer model (e.g. Nampak et al. 2014; Park et al. 2014), weight of evidence (e.g. Lee et al. 2012a), evidential belief function (e.g. Mogaji et al. 2016) and *Machine Learning Models* using artificial neural network (e.g. Lee et al. 2012b), boosted regression tree (e.g. Naghibi and Pourghasemi 2015), classification and regression tree (Naghibi and Pourghasemi 2015) and random forest models (Naghibi et al. 2017). Many newer models are continually introduced in groundwater potential mapping such as multivariate adaptive regression spline model (MARS) (Zabihi et al. 2016), maximum entropy model (Rahmati et al. 2016), generalised additive model (GAM) (Falah et al. 2016) and K-nearest neighbour (KNN) model (Naghibi and Dashtpazgerdi 2017).

Groundwater potential maps produced from these models based on different parameters influencing the flow and

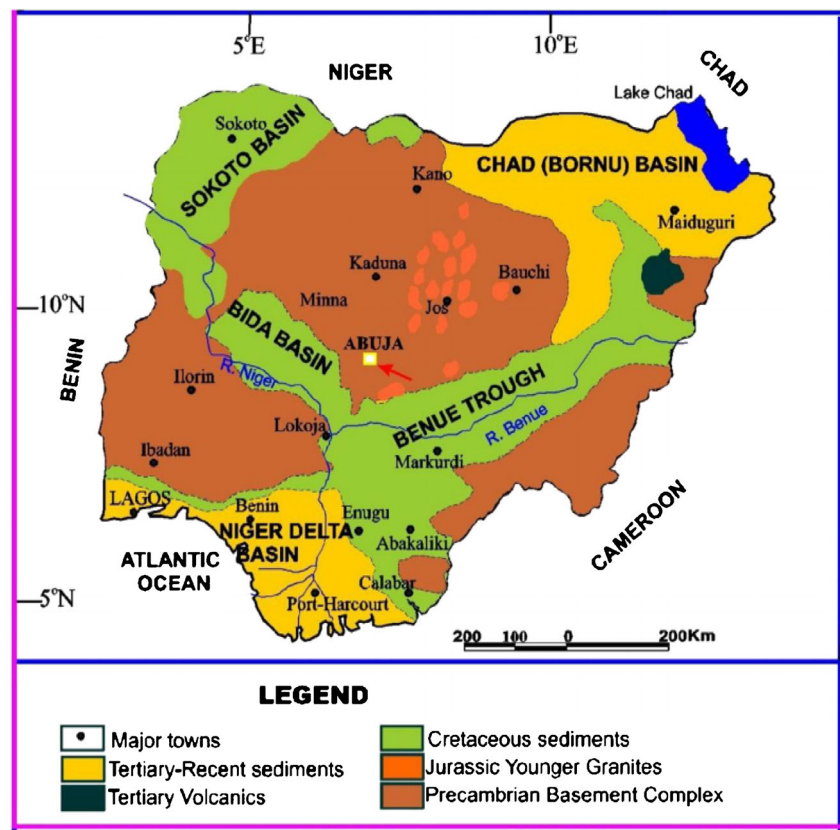
accumulation of groundwater serve as systematic guides to controlled planning, development and management of the resource (Khalil and Mebius 1991). Many Counties and regions of the world have groundwater maps that guide decision makers, planners as well as groundwater managers in the allocation, development and management of the resources (Elbeih 2014). These maps do not exist for many parts of Nigeria as the application of remote sensing and GIS technology in groundwater hydrology has received very little attention hence, low documentation. The reasons for this might not be unconnected to lack of adequate understanding of the role of geospatial technology in the development process, shortage of trained manpower, financial challenges of acquiring remotely sensed data and inadequate hardware and software facilities for image processing (Abiodun 2000). This paper therefore aims to provide a review on the application of remote sensing and GIS technologies to groundwater studies in Nigeria. Such a review is hoped to bring to bare the successes and most importantly the challenges faced by such studies and provide recommendations for improvement.

The study area

Nigeria is situated in West Africa, bordered by Niger Republic in the north, Chad Republic in the northeast, Benin Republic in the west, Cameroon in the east and the Gulf of Guinea in the south (Fig. 1). The terrain is very variable, with mountains in the southeast, hills and plateaux including the Jos Plateau in the centre, lowlands in the south and plains in the north (Tijani et al. 2016). The entire country lies on longitudes 2°50' to 14°20'E and from latitudes 4°10' to 13°48' N, occupying a land area of about 923,768 km² (Adelana et al. 2008). The climate varies from equatorial in the south to tropical in the centre and arid in the north. Annual rainfall varies from over 4000 mm in the south to less than 250 mm in the north, the national average being 1180 mm. Rainfall is seasonal with a wet season occurring between July and September in the north, extending to between April and November in the delta area (Tijani et al. 2016). The geology can broadly be divided into two major rock types viz. basement complex and sedimentary successions (Akujieze et al. 2003).

Basement complex and fluvio-volcanics comprising metasediments, schists, granites, basalts, gabbros, syenites, trachytes and rhyolites, largely of Precambrian to Tertiary to Recent volcanic. This complex is part of the Pan-African Mobile Belt lying between the West African Craton and the Congo Craton. It covers about 50% of the surface area of the country (Obaje et al., 2005) and outcrops in parts of northwest, northeast, southeast and the largest outcrop is in north central where Younger Granites of Jurassic age with characteristics ring complex structure intruded the basement (Adelana et al. 2008).

Fig. 1 Nigeria showing distribution of broad lithology (After MacDonald et al. 2005)



Sedimentary basins-rocks of Cretaceous-Tertiary and younger rocks composed mainly of sandstones, sands, silts, clays, shales, mudstones and limestone (Akujieze et al. 2003). This sedimentary succession covering about the remaining land surface of Nigeria is deposited in about eight structural basins (Eduvie 2006) namely, Sokoto basin (North West), Chad basin (North East), Middle Niger (Nupe basin), Anambra basin (South East), Benue basin (Benue trough), Niger Delta basin (South-South), Hadejia basin (West of Chad basin) and Dahomey basin (South Western Coastal basin).

This geological framework is, to a large extent, responsible for the distribution of groundwater in Nigeria (British Geological Survey, 2005; Adelana et al. 2008). There is a large groundwater potential in Nigeria which according to Akujieze et al. (2003) is estimated at 50 million trillion litres/year with annual estimated recharge of about 155.8 billion cubic metres per year. This by far exceeds the surface water resources of the country which is estimated at about 224 trillion litres/year. The two main types of groundwater are pore-type water in sedimentary cover and fissure-type water found in crystalline rocks (Eduvie 2006). In the crystalline basement areas, groundwater availability depends on the development of thick soil overburden (overburden aquifers) or the presence of fractures that are capable of holding water (fractured crystalline aquifers). The groundwater resources

here are usually limited and further compounded with challenges of adverse climatic conditions of aridity and semi aridity (Akujieze et al. 2003). The groundwater found in sedimentary deposits is mainly the pore-type, so also the ones found in alluvial deposits where aeolian and fluvial sediments are found. These collectively formed primary aquifers because the water is contained in their primary pore spaces. Among the biggest water bearing sedimentary units are Chad, Kerri-Kerri, Nsukka, Benin and Abeokuta Formations. This is because they are largely formed from sandstones, alluvial deposits and other related arenaceous sedimentary rocks. Shales, clays, limestones are generally poor aquifers due to their argillaceous nature. There is little groundwater in them, and the one found is only confined to their fracture and weathered zones. These rocks only help to confine an aquifer (Eduvie 2006).

Overview of RS and GIS in groundwater potential mapping around the globe

Remote sensing applications to groundwater investigation was realised quite lately because of the obvious reason that groundwater lies in the subsurface and out of reach of remote sensing devices to detect (Elbeih 2014). Its application only started in the 1960s where aerial photographs and satellite

images (visible and near infrared) were utilised in groundwater exploration with limited success (Jha et al. 2007). On the other hand, the use of GIS only began in the late 1980s with groundwater flow modelling (Watkins et al. 1996; Jha et al. 2007). Eventually, the use of aerial photographs in groundwater hydrology started to pave way for satellite imagery in the 1980s as advancement in sensor technology provided high-resolution spatial and multi-spectral imageries (Meijerink 1996). High-resolution satellite imageries aided the identification of surface features associated with groundwater storage and recharge such as lineaments (fractures, faults, bedding planes), topographic slope, natural vegetation, geologic landforms, drainage pattern and density etc. (Todd and Mays 2005; Becker 2006). However, satellite imageries are most useful when they are fed into GIS for integration with other datasets and analysed together to discriminate between groundwater promising areas from non-promising ones for further field surveys. Unlike decades ago, several standardised GIS coverages for groundwater hydrology (e.g. ArcGIS, ENVI, Erdas Imaging, SAGA etc) are now available, prompting more advances and diverse modelling types for groundwater. Currently, remote sensing is playing only a trivial role in groundwater potential mapping as very few datasets (lineament and land use) are now extracted from imageries. Bulk of the data now comes from existing database (geological maps, topographic maps, well locations and yields, geo-electric data, drill data etc) where they are integrated in GIS. The current status of RS and GIS applications in groundwater potential mapping around the globe are summarised in Table 1 below.

RS and GIS application to groundwater potential mapping in Nigeria

The use of remote sensing to analyse surface indicators of groundwater dates back to mid 1990s when Edet et al. (1996) applied aerial photographs and radar imagery to delineate areas suitable for groundwater development in Obudu Plateau and Oban Massif, Southeast Nigeria. The use of satellite imagery and GIS came a bit later when Bala et al. (1999) utilised imagery from Landsat-5 TM to extract information on land cover, vegetation lushness and lineament density in ER-Mapper to plot the first groundwater potential map of Dutsin-Ma, Katsina State. Satellite imagery, digital in nature have many advantages over photographs such as its multi-spectral resolution capability and ability to be easily stored and processed by computers (Teewu et al. 2005). In the succeeding years, the country's first Earth Observation Satellite NigeriaSat-1 was launched in 2003 (Asiyanbola 2014) to among many other objectives, study the country's environment and its resources. The satellite carries optical imaging payload that provided a 32-m spatial resolution and

swath width of about 640 km and uses the green, red and near infra-red bands equivalent to that of Landsat EMT+ bands 2, 3 and 4. One would expect that the satellite launch would usher in more data availability and spark interest among researchers in groundwater hydrology and indeed many other fields. But rather than increase, there seemed to be complete paucity of literature not until about a decade later when few studies began springing up. Till date, only one study had utilised data from NigeriaSat-1 and none from the subsequent satellites launched for application in groundwater potential mapping.

The application of GIS became prominent after the literature inert period and it provided a platform to integrate data from conventional ground based surveys with remote sensing data. Among the revolutionary studies were the work of Talabi and Tijani (2011) and Mogaji et al. (2011) that employed ArcGIS and ENVI, respectively. GIS application also brought about an upsurge in the number of surface indicating parameters analysed for groundwater potential mapping. From only two parameters in the pre GIS era to a maximum of 11 factors have so far being analysed in a single study. However, many of the models produced were seldom validated due to scarcity of well and spring data but quite recently, a number of studies have utilised well yield data for validation while others have adopted other indirect means of validation such as the use of geo-electric data, rock-type distribution (Nwachukwu et al. 2013) and water column from wells (Akinlalu et al. 2017). At present, a greater number of investigations concentrate in the south-western region, thus emphasising the need for similar studies in other regions of the country. A summary of just about all published literature from Nigeria in presented in Table 2 (Fig. 2).

Parameters of groundwater potential map

Parameters or conditioning factors that influence the movement and storage of groundwater used in preparing potential maps can be divided into two viz. regular and non-regular parameters. The regular parameters are usually extracted from remote sensing imageries and may include lithology, lineament (frequency and density), drainage (pattern and density), geomorphology, land use, land cover, slope angle vegetation index (NDVI) and topography. Non-regular parameters on the other hand are both sourced from remote sensing and ground-based surveys and may comprise parameters such as topographic wetness index (TWI), water divide zone, stream power index (SPI), storagivity, infiltration rate, transmissivity, specific yield, overburden thickness, aquifer thickness, etc. These parameters can be adopted for any study based on interest or the datasets available. However, some parameters are site or region specific as they improve prediction rate for only such sites or region. For instance, Karstic domain parameter was used for a region underlain by carbonate rocks (Shaban et al.,

Table 1 Summary of the current status (within the last 5 years) of RS and GIS application in groundwater mapping around the Globe

Author(s)	Study area	Imagery and GIS	Model	Result and comments
Singh et al. 2013	Nasik, India	(i) IRS-ID (LISS III) (ii) ERDAS Imagine (iii) ArcGIS (i) ASTER DEM	Weighted Index Overlay	Model could be subjective, validity conducted without accuracy assessment.
Konkul et al. 2013	Huay Sai, Thailand	(i) ASTER DEM	Weighted Index Overlay	Reduce subjectivity by adopting weights from literature. Zone boundary too sharp.
Deepika et al. 2013	Gangolli basin, India	(i) IRS-1C (LISS III) (ii) SRTM DEM (iii) ERDAS Imagine (iv) ArcGIS (i) Landsat-5 TM	Weighted Index Overlay	Prioritisation of morphometric parameters revealed areas of surplus and deficit groundwater potential. No validation.
Park et al. 2014	Boryeong and Pohang, Korea	(i) Landsat-5 TM	Evidential Belief Function	Degrees of belief showed higher importance of lower elevation, gentle slope and lineament density. Validity showed high accuracy of the EBF model.
Rahmati et al. 2014	Kurdistan Iran	(i) ASTER DEM (ii) Landsat-7 ETM+	Analytical Hierarchy Process	73.6% validation accuracy. Model can be subjective with inputs from experts.
Fenta et al. 2014	Raya Valley, Ethiopia	(i) Landsat-7 ETM+ (ii) ASTER DEM	Analytical Hierarchy Process	Good validation with borehole yield that showed 74% validity. Model somewhat subjective.
Ahmed et al. 2015	Balochistan, Pakistan	(i) ASTER DEM	Catastrophe theory	Lineament factor not considered and no statistical approach to map validation.
Nag and Saha 2014	West Bengal, India	(i) IRS-1C (LISS III)	Weighted Index Overlay	Lithology not considered, no ground truth and model validation. Model itself is subjective.
Razandi et al. 2015	Tehran Province, Iran	(i) ASTER DEM	Analytical Hierarchy Process, Frequency Ratio, Certainty Factor models	FR (77.55%) and AHP (73.47%) showed better accuracy than CF (65.08%) using the ROC curve validation. Groundwater potential zones controlled by aquifer thickness, rainfall and lithology. Model combination proves better result.
Al-Ruzouq et al. 2015	Northern part of UAE	(i) ASTER DEM	Analytical Hierarchy Process	Study area mostly covered by low groundwater potential zones. No validation and model is somewhat subjective.
Pinto et al. 2015	Comoro, Timor Leste	(i) Landsat 5 TM	Analytical Hierarchy Process	High groundwater potential is a reflection of rainfall amounts, geology and slope function. Good validation with well yield.
Rajaveni et al. 2015	Telengana, India	(i) IRS P6 LISS IV	Weighted Index Overlay	Reduced subjectivity as weightings were assigned based on reviewed literatures.
Liu et al. 2015			Analytical Hierarchy Process	Validation with groundwater atlas good for data scarce areas.

Table 1 (continued)

Author(s)	Study area	Imagery and GIS	Model	Result and comments
	Alberta, Canada	(i) MICRODEM M		
Tahmassebpour et al. 2016	Ilam Plain, Iran	(ii) ArcGIS (i) Landsat ETM+ (ii) ArcGIS (iii) ENVI	Weight of Evidence (Woe) and Evidential Belief Function (EBF) Models	Model comparison shows Evidential Belief Function performing better than Weight of Evidence.
Nejad et al., 2017	Azna Plain, Iran	(i) Landsat ETM+ (ii) ArcGIS (iii) ENVI	Weight of Evidence (Woe) and Evidential Belief Function (EBF) models	Both models performed good prediction. Models have high data demand and could be difficult to use in data scarce regions.
Rahmati et al. 2016	Mehran, Iran	(i) Landsat-7 ETM+ (ii) ArcGIS (iii) ENVI	Random Forest (RF) and Maximum Entropy (ME) models	ME model performed excellent prediction and validation. Well data does not cover all parts of study area.
Park et al. 2017	Korea	(i) Korea Multi-Purpose Satellite-2 (ii) ArcGIS (iii) PCI Geomatica	Linear Regression (LR) and Multivariate Adaptive Regression Spline (MARS) models	Both models provided excellent validation for groundwater map.
Naghbi and Dastpazgerdi 2017	Khalkha, Iran	(i) Landsat-7 ETM+ (ii) ArcGIS (iii) SAGA	K-Nearest Neighbor (K-NN), Linear Discriminant Analysis (LDA), Multivariate Adaptive Regression Splines (MARS) and Quadratic Discriminant Analysis (QDA)	Springs wells covered most parts of study area and all models provided excellent validation but MARS and QDA proved better.
Hou et al. 2017	Ningxiaota, China	(i) Landsat-7 ETM+ (ii) ArcGIS	Statistical Index (SI), Index of Entropy (IOE) and Certainty Factor (CF) models	Models showed excellent validation especially for IOE, but spring wells do not cover the entire area of study.
Lee et al. 2017	Boryeong, Korea	(i) Landsat TM (ii) ENVI (iii) ArcGIS	Artificial Neural Network (ANN) and Support Vector Machine (SVM) models	Machine learning models also proving excellent in groundwater potential prediction
Díaz-Alcaide et al. 2017	Mali	(i) QGIS	Weighted Index Overlay	Study not applicable in data scarce region. Weighting method highly subjective.
Guru et al. 2017	Cold desert, India	(i) IRS (LISS IV) (ii) ASTER DEM	Frequency Ratio (FR)	Wells used as training dataset and for model validity are not wide spread, hence can affect the model accuracy.

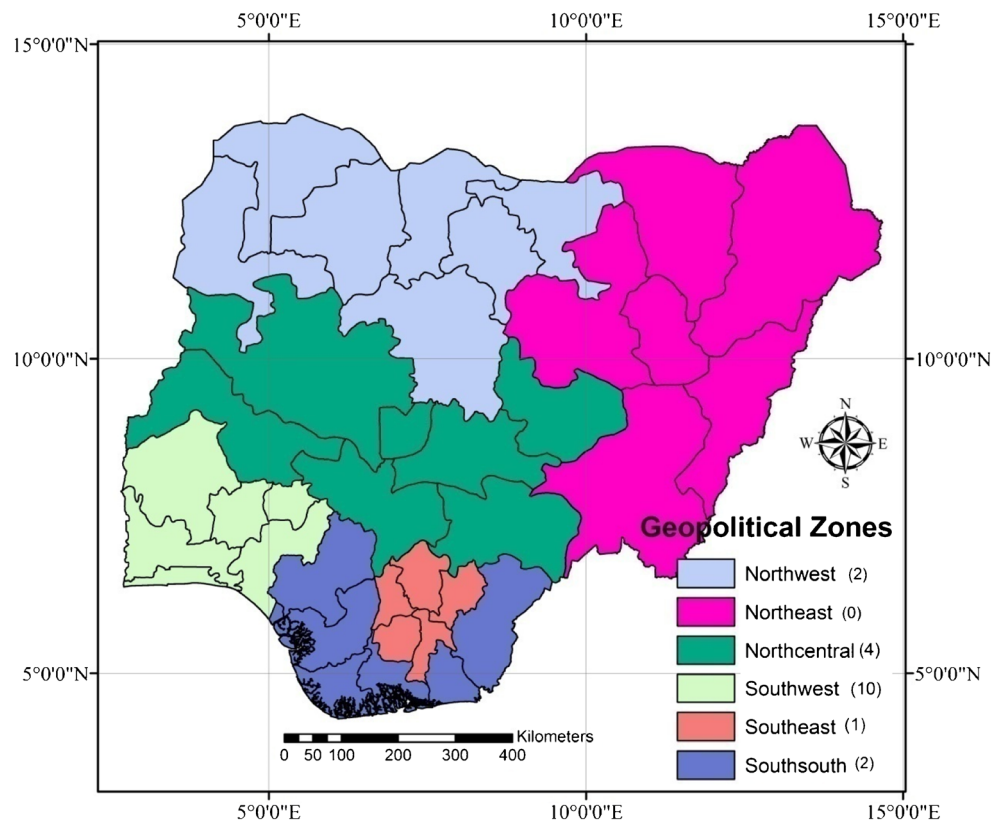
Table 2 Summary of literature on RS and GIS application to groundwater mapping in Nigeria

No.	Author(s)	Study area	Imagery and GIS	Model	Result and comments
1.	Edet et al. 1996	Obudu and Oban Massif, South-South Nigeria	(i) Black and white radar imagery (ii) Pan aerial photos	–	Relationships between lineament length density, water temperature, conductivity, well yield, transmissivity and longitudinal conductance showed the effects of secondary permeability. No validation
2.	Bala et al. 1999	Dutsin-ma North-West Nigeria	(i) Landsat 5 TM	GIS overlay	Lineaments trends show two major maxima. Favourable zones controlled by lineaments, lithology and soil/rock texture. No validation.
3.	Mogaji et al. 2011	Ondo South-West Nigeria	(i) Landsat 7 ETM+ (ii) ASTER DEM (iii) ENVI	GIS overlay	Areas with long and cross-cutting lineaments are feasible zones of groundwater prospecting. No validation
4.	Talabi and Tijani 2011	Ekiti, Southwest, Nigeria	(i) Landsat TM (ii) NigerSat-1 imagery (iii) Aeromagnetic map (iv) ArcGIS	Weighted Index Overlay	Weightage assigned based on literature. Very good potential zones underlain mostly by granitic/chamockitic rocks. Good validation with borehole yields.
5.	Anifowose and Kolawole 2012	Akure Southwest, Nigeria	(i) Landsat ETM+ (ii) ILWIS	GIS overlay	E-W lineament orientation exerts greater control on the direction of groundwater flow. No validation
6.	Fashae et al. 2013	Basement of Southwest Nigeria	(i) Landsat ETM+ (ii) STRM DEM (iii) ArcGIS (iv) Idrisi	Analytical Hierarchy Process	Geology has the greatest influence followed by morphology in the delineation of the potential zones. Borehole/well yields showed good validation but without statistical description.
7.	Abdullahi et al. 2013	Kebbi, Northwest, Nigeria	(i) Landsat TM (ii) SRTM DEM (iii) ILWIS (iv) ArcGIS	Weighted Index Overlay	Areas with low slope, high lineament density and low altitude constituted the best potential zones. Poor validation method with no statistical description.
8.	Nwachukwu et al. 2013	Imo River Basin, Southeast, Nigeria	(i) SLAR (ii) Surfer 8	GIS overlay	Groundwater prospect map shows strong influence of geology. Groundwater prospects increases from north to south. Poor validation with rock-type distribution.
9.	Alagbe et al. 2013	Iwo, Southwest, Nigeria	(i) Landsat TM (ii) SRTM DEM (iii) ArcGIS (iv) Erdas Imaging	–	Long lineaments and high conductivity values of VLF indicate zones of deep weathering and good sites for groundwater development. No validation.
10.	Bayowa et al. 2014b	Ekiti, Southwest Nigeria	(i) Landsat TM (ii) SRTM DEM (iii) ArcGIS (iv) Erdas Imaging	GIS overlay	Groundwater potential generally low to moderate. Thick overburden areas have shallow depth to groundwater. Validation with borehole yield, no statistical approach.
11.	Bayowa et al., 2014a	Ekiti, Southwest Nigeria	(i) Landsat TM (ii) SRTM DEM (iii) ArcGIS (iv) Erdas Imaging	Weighted Index Overlay	Lineament density and lineament density cluster maps were produced to model groundwater potential but no validation
12.	Sikakwe et al. 2015	Oban Massif, South-south Nigeria	(i) Landsat ETM+ (ii) ASTER DEM (iii) SRTM DEM (iv) ArcGIS, ENVI	Weighted Index Overlay	Order of groundwater controlling factors is geology, slope and lineament. Sedimentary areas have greater potentials. No validation

Table 2 (continued)

No.	Author(s)	Study area	Imagery and GIS	Model	Result and comments
13.	Ejebu et al. 2015	Paiko, North-central Nigeria	(v) PCI Geomatica (i) Landsat ETM+ (ii) SRTM DEM (iii) ArcGIS	Analytical Hierarchy Process GIS overlay	Vegetated areas delineated as poor zones. No validation for model.
14.	Amigun et al. 2015	Okene, North-central Nigeria	(i) Landsat 5-TM (ii) ILWIS	GIS overlay	Strong correlation between lineament density, total magnetic intensity and weathered regolith thickness. No validation.
15.	Kolawole et al. 2016	Osara, North-central Nigeria	(iii) Landsat MSS (iv) ILWIS (v) Surfer-8	GIS overlay	Few parameters assessed, zone boundaries too sharp and no validation.
16.	Akinwumiju et al. 2016	Osun, Southwest Nigeria	(i) Landsat 8 (ii) SPOT (ii) ASTER DEM	Weighted Index Overlay	Lineament density and lithology (foliated metamorphic rocks) exert greatest influence in groundwater storage. Strong correlation of model with well yield data
17.	Akinlalu et al. 2017	Oke-Ana, Southwest Nigeria	(i) Landsat 5-TM (ii) PCI Geomatica (iii) ArcGIS	Analytical Hierarchy Process Analytical Hierarchy Process	Validation with water column due to data scarcity and highlighted reasons behind failed groundwater projects in the past.
18.	Ejebu et al. 2017	Paiko, North-central Nigeria	(i) Landsat ETM+ (ii) SRTM DEM (iii) ArcGIS	Analytical Hierarchy Process Weighted Index Overlay	High yields in areas where wellbore intersect with fractures or in places with deeply weathered residuum. No validation
19.	Adeyemi and Anifowose 2017	Owo, Southwest Nigeria	(i) Landsat ETM+ (ii) SRTM DEM (iii) ERDAS Imaging (iv) ENVI (v) ILWIS	Weighted Index Overlay	Biased Thematic layer weighting, unclear map legend and no validation.

Fig. 2 Nigeria showing spatial distribution of groundwater mapping studies using remote sensing and GIS across the geopolitical regions



2005). Tropical savannah regions with concentration of epigeal nests constructed by ecosystem engineers can adopt nest locations as a parameter as they are reported to improve dry-land robustness against drought and are even suggested to indicate the presence of groundwater (Bargués Tobella et al. 2014; Mège and Rango 2009).

Parameter extraction methods and common challenges faced by studies in Nigeria

Lineaments

Lineament is the most common and often most important parameter employed in groundwater potential mapping. Lineaments are naturally occurring alignment of soil, topography, stream channels, vegetation or a combination of these features that are visible on remotely sensed imageries (Alagbe et al. 2013). They are long and linear to curvilinear geologic structures (joints, faults and folds) which may be represented on the earth surface as ridge lines, depressions lines, alignment of vegetation and drainage courses. They are a reflection of the subsurface geology of an area and are important in enhancing secondary porosity in rocks thus influencing weathering, soil erosion and groundwater movements (Edet et al. 1996). Some studies have shown high well yields with short distances from lineaments (e.g. Hammouri et al. 2012; Chuma

et al. 2013; Senthil Kumar and Shankar 2014) while it was not true for others (e.g. Fashae et al. 2013; Jasrotia et al. 2012). Lineaments are extracted either manually or automatically from imageries. In manual/visual interpretation, lineaments can be drawn by hand on an overlay of an analogue image under the stereoscope (Ramli et al. 2010; Tirén 2010) or on the screen of a computer (Tirén 2010). Drawing by hand has the advantage of being quick and takes a real geologic form while drawing on the screen has the advantage of using the full image resolution (Tirén 2010). However, there are a number of shortcomings associated with manual interpretation. They include subjectivity and non-reproducibility (interpreter bias) and inadequate lineament detection due to direction of illumination (Raghavan et al. 1995; Meijerink 2007; Ramli et al. 2010). Most researchers are aware of these shortcomings and some make mention of them in their work (e.g. Shaban et al. 2005) but measures to address them are not usually employed or not stressed.

To overcome the problem of subjectivity, Tirén (2010) proposed interpretation by multiple (6) observers or multiple times (6) of interpretations be done to get information about uncertainties in the positions and length of the lineaments. The lineaments that occur in at least three to four out of six interpretations are then chosen. On the basis of direction of illumination source, the use of digital elevation data has been shown to offer the possibility of revealing features not apparent in regular satellite images (Raghavan et al. 1995). This is

because a digital elevation model (DEM) could be artificially illuminated from any desired direction, which is not possible in optical satellite imagery. This capability is important where the lighting may be in a perpendicular direction in order to enhance any suspected lineament (Ramli et al. 2010). Review has shown that no study had taken extra step to lessen interpreter bias and only a few studies overcame the second challenge by draping DEM on already processed image for the extraction of lineaments (Mogaji et al. 2011; Bayowa et al. 2014b; Ejepu et al. 2017).

In automatic interpretation, there is the elimination of subjectivity as it uses computer algorithms (Meijerink 2007; Ramli et al. 2010) such as Hough transform (Karnieli et al., 1996) and extraction algorithm of PCI geomatica. However, the major problem is that such algorithms operate purely on linearity contrast in an image. Thus, many features not associated with fractures, such as man-made boundaries (field boundaries, roads, fences, etc.), strike ridges, foliation directions and so on, are included. This leaves the interpreter with the task of establishing one after the other which lineaments are associated with possible fractures and which are not (Meijerink 2007). This requires the interpreter to have a good knowledge of the study area. In recognition of the tedious nature of filtering out false lineaments, only a few studies adopted automatic interpretation (Sikakwe et al., 2015; Akinwumiju et al. 2016). Another possible reason might be the absence of automatic linearity extraction from regular image processing softwares as most of the programs are in standalone softwares with PCI Geomatica being about the only exception (Ramli et al. 2010). This explains why most of the studies that utilised automatic interpretation made use of the line module of PCI Geomatica.

Drainage

Drainage is an important agent of hydrogeological control. Drainage patterns are reflections of surface and subsurface formations (Jaiswal et al. 2003; Prasad et al. 2007), while drainage density is an inverse function of permeability where generally, high drainage density implies low void ratio and consequently low rate of infiltration and vice versa (Murthy 2000; Jaiswal et al. 2003). In comparing different formations or localities, the one that contains the greatest drainage density is usually less permeable and indicates a poorer groundwater potential (Edet et al. 1996). However, Sener et al. (2005) and Shaban et al. (2005) showed that not all high drainage density areas have low infiltration or recharge rate and as such, great care should be exercised in the categorisation.

Drainage, like lineaments, can be extracted manually or automatically from remotely sensed images (Shaban et al. 2005), but review has shown that studies prefer to extract the drainage manually either from topographic maps, aerial photos, satellite images, digital elevation model (DEM) or a

combination of these. This is probably because of the same challenges associated with automatic lineament extraction and coupled with the fact that drainage network is much easier to interpret manually especially with familiarity of the area of study. Usually, researchers grid their maps when calculating drainage density and frequency, while few others use sliding windows (frames of specific area) (Shaban et al. 2005). From each grid or frame, the drainage lines are measured and converted to the map scale to arrive at the drainage length. The drainage length is then divided by the area of the grid or frame to arrive at the drainage density. A drainage density map is prepared to indicate areas of high and low density. The importance of drainage density as a controlling factor to groundwater infiltration process is reflected in many studies. Only few studies, Mogaji et al. (2011) and Alagbe et al. (2013), ignored this important parameter.

Lithology

The pattern, texture and density of drainage as well as that of lineaments are controlled by the underlying lithology (Edet et al. 1996). Remote sensing provides an easy and cheap way to map the geology of an area by visually tracing many lithological patches and their boundaries. However, this must be combined with ground truth, providing additions or corrections to the image earlier interpreted. The most common satellite imageries utilised for mapping lithology are the Landsat series with standard colour composite combining bands 1, 4 and 5 (Solomon and Quiel 2005) and bands 7, 4 and 1 (Sener et al., 2005), IRS (LISS) IV combining standard colour composites of bands 1, 4 and 5 (Rajaveni et al. 2015) and aerial photographs for their stereoscopic effect (Yeh et al., 2009). Despite the higher spatial resolution of NigeriaSat-2 (5 m multispectral and 2.5 m panchromatic) compared to Landsat ETM (30 m multispectral and 15 m panchromatic) and IRS (multispectral ranging from 5.8 to 56 m), no research from Nigeria utilised imageries from the Nigeria satellite for this purpose. However, as most regions of the world have been covered with geological surveys, researchers prefer to use digitised maps provided from such surveys.

Geomorphology

Geomorphology here refers to the various landforms and topographical features that are important in planning and execution of groundwater exploration (Fashae et al. 2013). Changes in surface topography affect the depth to the water table and direction of groundwater movement, rainfall intensity and consequently, affect the permeability, porosity and infiltration rates (Al-Abadi and Al-Shamma'a 2014). Geomorphology is very important as it is found to be the most influential factor in a number of studies (Jasrotia et al. 2007; Sajjad et al. 2014). How landform is categorised depends on

the structural complexity of the study area, but is generally divided into high lands, plains and low lands, with low lands having better prospect to store groundwater (Teixeira et al. 2008). Landforms are delineated manually from visual interpretations of topographical maps, aerial photographs, satellite imageries, digital elevation models or their combination. Best results are obtained from a combination of either digitised topographic map or ortho-rectified aerial photographs or satellite image with a digital elevation model to achieve a 3D visualisation. This improves the understanding of the spatial relationships between image texture and topography thus allowing land features to be observed from vertical view at different scales and from different orientations (Mohamad et al. 2005). Only seven studies considered geomorphology and is either interpreted from DEM or satellite images with only four of the studies combining both DEM and imagery for better result (Talabi and Tijani 2011; Fashae et al. 2013; Sikakwe et al. 2015; Ejepu et al. 2015; Adewumi and Anifowose 2017).

Slope

Slope measured in degree or percent refers to the rate of change in height across a surface region (Manjare 2014). It influences the infiltration or otherwise of surface water into the subsurface (Manjare 2014; Fenta et al. 2014). Flat to gentle slope areas provide more time for water to remain on the surface thereby promoting infiltration, whereas high slope areas allow lesser residence time of water on the surface resulting in runoff and low infiltration (Sener et al., 2005; Hammouri et al. 2012; Fashae et al. 2013). Slope can be extracted either from digital elevation models (e.g. ASTER and STRM DEMs) (Jasrotia et al. 2012; Deepika et al. 2013; Fashae et al. 2013; Sikakwe et al. 2015) or from topographical contours and survey base points from where a DEM can be generated (Pradhan, 2009; Razandi et al. 2015). After extraction, slope gradient is categorised into different classes ranging from nearly flat level to very steep slope depending on the study choices, but one of the most suitable classification is that standardised classification according to Integrated Mission for Sustainable Development Technical Guidelines (IMSD) India (Manjare 2014) and Ministry of Natural Resources and Environment (NRE), Malaysia. These classifications group slope gradient into about six classes namely, nearly flat level (0–5°), very gentle slope (10–15°) gently sloping (15–25°), moderately sloping (25–35°), strongly sloping (35–60°) and very steep slope (61–90°).

Studies in Nigeria seldom use the slope factor, and when used, the classification is according to study choice (4–5

classes are commonly used) as no guideline classification is reported for Nigeria.

Land use/land cover

Land use/land cover pattern is a significant factor that control infiltration and runoff (Shaban et al. 2005; Kumar et al. 2010). Agricultural and plantation lands for example could be excellent sites for groundwater exploration (Sajjad et al. 2014), as trees and plants can trap water on foliage causing it to infiltrate through the roots to recharge groundwater. Also, BARGUES Tobella et al. (2014) revealed that surface water flow preferentially under trees and that could enhance greater infiltration. Settlements on the other hand serve as poor groundwater areas due to the use of concrete floors that only allows surface runoff (Sikakwe et al. 2015). Land use/land cover pattern is usually mapped from remotely sensed data and a combination of topographic map and field verification. Using satellite imagery, a false colour composite (FCC) is usually generated using various band combinations such as IRS bands 1, 2 and 3 (Pradhan, 2009), and Landsat ETM bands 4, 3 and 2 (Fashae et al. 2013; Fenta et al. 2014; Chuma et al. 2013). This is followed by visual identification of the land use/land cover pattern after which training sites are selected for supervised classification. In other cases, studies employ land use/land cover maps already prepared by government agencies only to digitise them and make appropriate classification (Pinto et al. 2015). Only five studies recognised the importance of land use/land cover in this regard (Fashae et al. 2013; Sikakwe et al. 2015; Ejepu et al. 2015; Adewumi and Anifowose 2017). These studies interpreted the land use/land cover patterns from Landsat imageries as ready-made copies are not common and not readily available except probably for major cities like Abuja and Lagos.

Weight assignment

Weight can be said to be the strength or relative degree of importance of one parameter/thematic layer over another or a class under a parameter over another as regards their influence to groundwater storage. There is currently no standard weights for parameters and their classes (Saraf and Choudhary, 1998) as such many studies assign weights based on their judgements. This creates room for assumptions and human bias. Efforts are made by other studies to limit self-judgement by incorporating views of several experts in what is referred to as knowledge-driven approach, others by measuring the relative major and minor interrelationship of one parameter over another (Shaban et al. 2005; Akinwumiju et al. 2016). Another approach that has gained acceptability because of its ability to eliminate human bias is the Multi-criteria Decision Analysis (MCDA). The MCDA is an advanced field in operation research that addresses

complex decision problems involving multiple criteria. The commonly used MCDA is the analytical hierarchy process (AHP) developed by Saaty (1980) and less commonly Catastrophe theory (Ahmed et al. 2015). The AHP is the most widely accepted method for scaling rates and weights of parameters/thematic layers and their classes (Fenta et al. 2014) by allowing the decision maker to place his/her judgements in order of priority. In addition, a test of consistency of the judgement is assessed by a consistency ratio (CR) where ratings greater than 0.1 are re-evaluated. The popularity of AHP is probably because it is about the only Multi-criteria Decision Analysis based on GIS. Another method of weight assignment is through literature findings.

A considerable number of studies in Nigeria preferred not to assign weight to thematic layers as wells as classes in the thematic layers. The reason for this might not be unconnected with the type of GIS software used (mostly ILWIS) as it might not provide a platform for weight assignment. However, four weight assigning methods have been adopted. These include personal judgement (Bayowa et al. 2014b; Adewumi and Anifowose 2017), adoption from literature (Talabi and Tijani 2011), major and minor interrelationship of parameters (Akinwumiju et al. 2016) and AHP (Fashae et al. 2013; Ejepu et al. 2015, 2017).

Remote sensing-GIS integration methods

Gao (2002) summarised the methods used in integrating remote sensing, GIS and GPS data into four namely; linear models (LM), interactive models (IM), hierarchical models (HM) and complex models (CM). Linear models are most preferred for groundwater potential mapping (Thakur et al. 2016) owing to their non complexity and less data demand even though they could be subjective. The main linear model in use is the GIS-based weighted overlay analysis. However, many studies from Nigeria chose not to weight thematic layers and instead integrate them using only simple overlay. Hierarchical models are now widely accepted using the multi-criteria decision analysis and most popularly the analytical hierarchy process. The major advantage of this model is that it tends to reduce subjectivity in weight assignment and subsequent layer overlay through the contribution of experts judgements.

Statistical models and machine learning models are quite complex and can be categorised under complex models. These models are increasingly been adopted in recent times and include frequency ratio model (e.g. Oh et al. 2011; Razandi et al. 2015; Guru et al. 2017), logistic regression model (e.g. Ozdemir 2011; Pourtaghi and Pourghasemi 2014), Dempster Shafer model (e.g. Nampak et al. 2014; Park et al. 2014), weight of evidence (e.g. Lee et al. 2012a, b), evidential belief function (e.g. Mogaji et al. 2016), artificial neural network

(e.g. Lee et al. 2012a, b), boosted regression tree (e.g. Naghibi and Pourghasemi 2015), classification and regression tree (Naghibi and Pourghasemi 2015), random forest models (e.g. Naghibi and Dashtpargerdi 2017), multivariate adaptive regression spline model (MARS) (Zabihi et al. 2016), maximum entropy model (Rahmati et al. 2016), generalised additive model (GAM) (Falah et al. 2016) and K-nearest neighbour (KNN) model (Naghibi and Dashtpargerdi Naghibi and Dashtpargerdi 2017). These models have been proven to be satisfactory for groundwater potential mapping but nonetheless, require huge data on well and borehole yields and as such cannot be applicable in data scarce areas.

Thematic layer integration is achieved only by simple GIS overlay, weighted overlay analysis and AHP from studies in Nigeria. Probabilistic and machine learning models have never been attempted probably due to non availability of well data. A considerable number of studies utilised GIS software that resulted in creating sharp contrast or edges between boundaries of different potential zones which does not portray a realistic situation.

Model validation

Validation is an important step in a modelling process as without it, the model will lack scientific significance (Chung-Jo and Fabbri, 2003). The most accepted approach to validating groundwater potential map/model is the use of documented well and borehole yields data by overlying it on the model to verify the model result. Descriptive statistical analysis can then be performed to describe the percentage of, for example, high yield wells that fall in the high potential zones and vice versa (Fenta et al. 2014; Pinto et al. 2015). Statistical and graphical methods of validations are increasingly being employed. Some of these methods include receiver operating characteristics (ROC) and success and prediction rate curves. In these methods, the cumulative percentage of the potential map is plotted on x-axis against the percentage of groundwater occurrence on the y-axis. The area under curve (AUC) is then calculated to represent the accuracy of a prediction. These methods have proved to be quite reliable.

Other validation methods used in the absence of well yield data are aquifer thickness, overburden thickness (from VES), static water levels and well water column (e.g. Murthy 2000; Akinlalu et al. 2017). These validation methods, however, are good assumptions for regions without hydrogeological data. Other studies compare their results with that of previous studies (e.g. Shaban et al. 2005). Unfortunately, many investigations in Nigeria failed to provide model validations. From review, only six studies provided validations variously using borehole yields, saturated thickness, water column and borehole depth. Often, statistical approaches are not applied in the analysis.

Conclusion and recommendations

From literature, it is evident that the application of geospatial technology in groundwater studies in Nigeria is not only limited but also lacks standard. Models are produced using insufficient data, unsuitable software applications and in many instances without validations. Reasons can be attributed to various constraints including but not limited to restrictions on RS data (e.g. NigeriaSat imagery), absence or poor facilities and arrangements for data distribution and sharing between agencies and institutions, poor knowledge about the technology itself, inadequate facilities for trainings at undergraduate and graduate levels leading to insufficient skilled manpower, expensive nature of RS and GIS software packages and chronic scarcity of field data on groundwater due to lack of monitoring facilities. These challenges can be resolved when (1) the National Remote Sensing Agency of Nigeria makes available and affordable to the public RS data of NigeriaSat and data from many other satellites and making the acquisition process easy such as can be downloaded via a website to encourage research in this aspect. Imageries of NigeriaSat-2 from the spatial resolution point of view (5 m multispectral and 2.5 m panchromatic) might prove to be better in hydro-geomorphological information extraction compared to Landsat ETM (30 m multispectral and 15 m panchromatic) and IRS (multispectral ranging from 5.8 to 56 m), (2) improving the obsolete and inadequate facilities and providing up-to date software applications and other accessories at educational institutions and training centres and intensify awareness in the proficiency of RS and GIS in the development process, (3) develop groundwater monitoring facilities throughout the country and ensure strict adherence to groundwater development standards for both public and private concerns.

In conclusion, remote sensing has provided useful data on groundwater conditioning factors to complement the conventional invasive field data while GIS on the other hand has provided a platform for integration of data from these two sources to efficiently interpret groundwater conditions cost effectively. With the growing interest among Nigerian researchers, it would be important to make improvements in areas such as (1) quality and time of satellite data acquisition, as some factors controlling groundwater are better interpreted in a particular time or season. This timing is often ignored but Corgne et al. (2010) showed that dry season imagery is most promising for lineament extraction for example, as it is less affected by vegetation cover. (2) Other models should not just be tested but also used to make comparisons as to which are better for potential prediction given the limited data availability. (3) Efforts must be made at validating groundwater potential models to make any scientific sense. Data used for validation purpose have earlier been discussed in this review. Geophysical data from VES

soundings are fairly abundant in the country, but no potential assessment study has inferred optimum drill depth for the potential zones. Finally, the groundwater potential of many parts of the country especially the North-eastern part covered largely by sedimentary successions has not been assessed. Efforts should be intensified to cover the whole country. This will enable adequate planning, exploration and management of the precious resource in a sustainable way.

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