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Application of Geographic Information System (GIS) in sustainable groundwater development, Imo River Basin Nigeria

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There is proliferation of shallow substandard private water wells, poor distribution of public water wells, poor planning, and poor management of public wells in the Imo River basin Nigeria. Over 60% of water wells developed in the basin is either abortive or not functional. To investigate this, 110 vertical electric soundings (VES), 50 down-hole logs, and 44 pumping test data have been integrated into geographic information system (GIS) in this study. Map of 44 county areas of the basin was produced. Thematic maps showing mean values of water table, aquifer resistivity, aquifer thickness, and a groundwater prospect map of the basin in five potential areas were also produced. Correlating the GIS map with regional geologic map defined three groundwater prospect zones in the basin. Sustainable practices recommended are *government-private partnership* for public wells, and *private-private partnership* for private wells. Surface water development is recommended in zone 3, against groundwater development. Geophysics/GIS groundwater prospect model shows significant correlation with geology, confirming the effects of geology to groundwater development in the basin.

Key words: Private/Public water wells, geophysics data, geographic information system (GIS) models, abortive wells, geology, sustainability.

INTRODUCTION

Unavailability of groundwater prospect map of the basin area for public consumption is thought to have contributed greatly to the increasing failure of water well projects in certain parts of the Imo River basin Nigeria (Figure 1a and 1b). For example, groundwater prospect map is a vital tool to government in water well allocation decision making process. By this, individuals, organizations, communities, and governments could visualize areas mapped as difficult for groundwater development and then be committed to an alternative water sources in such areas. This will reduce incidents of failure, abortive, or abandoned public wells and non-functionality of domestic water wells estimated at over 850 in the basin. It is therefore very necessary to do everything possible that can reduce incidents of abortive wells, substandard domestic wells, and non-functional wells. With good groundwater prospect map, government would award contracts of water well projects to only viable areas, excluding areas where difficult subsurface geology does not allow successful groundwater development. Groundwater prospect map will allow fair distribution of public water wells to communities. Groundwater prospect map will reduce economic wastes, and environmental degradation, as well as disappointment and hardship to the affected communities; based on a model of distribution with no consideration for areas with

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Figure 1. Map of Nigeria showing Imo River basin.

groundwater development difficulty.

The result is economic waste, and environmental degradation, as well as greater disappointment to the affected communities. Citizens are therefore constrained to the proliferation of shallow substandard wells often recharged by surface water through fractures, and harvested rain water stored in ground tanks of all manners. This may be accountable to the persistence of water related diseases in the basin.

Proliferation of shallow private/commercial wells of poor standards by individuals also implies financial incapability for standard wells. This is due to lack of functional public water supply, and the excessive desire of citizens to be self dependent. The most contaminated wells are usually the shallow hand-dug rather than drilled, and having poor casing material (Comely, 1987). Incidentally most of the shallow private and commercial wells in the basin are hand-driven, and some constructed with inferior casings. According to Nwachukwu et al. (2010b), the greatest problem of manual drilling is the impunity at which the operators declare the drilling terminated, soon as the crew penetrates the water table, or run out of energy. Ibe et al. (2007), Nwachukwu et al. (2010a), and Nwachukwu et al. (2010c), have confirmed that environmental pollution in the Imo River basin increases from the shaly north to the sandy south. They hold that human activities also follow a similar trend, representing the primary source of water pollution in the Imo River basin. The final analysis implicates shallow wells in the sandy south to be more vulnerable to pollution than the equivalent in the north.

Geology

The basin is a 140 km N-S trending sedimentary syncline located at the mid south-eastern part of Nigeria (Figure 1). It is rich in oil and gas and has many of Nigerian oil fields. The basin has rich deposit of clay minerals, sand, gravel, and lignite. Based on near surface lithology, the Imo River Basin was divided into two zones (Nwachukwu et al., 2010a). The northern zone consisting of group of shale formations have greater drainage density, than the southern zone belonging to the sandy Benin Formation (Figure 10). Age of the shaly zone range from *paleocene* to *Albian,* and the sandy zone is *Olgocene* to *Recent*. Prospective horizon for groundwater development in the basin varies from location to location. Age and characteristics of the geologic units are discussed by Reyment (1965), Onyeagocha (1980), and Ekweozor and Unomah (1990).

Recent investigation confirmed the presence of 40 to 70 counts of coliform per 100 ml of water in six out of ten sampled shallow wells around Owerri (Nwachukwu et al., 2010b). This may have significant health implications. The average cost of treating severe typhoid fever and diarrhea (alias *stooling* and *vomiting*) to families which may result in sudden deaths is enormous. It is a major source of poverty, draining both the household and the state economy. The overall effects, including the loss of man hour in both public and private sectors is alarming, and difficult to be estimated due to lack of records. A recent survey has confirmed the presence of one or two abortive wells in the vicinity of three to five functional well in the area. Most of the private and public wells became abortive immediately on completion. Others became non-functional 2 to 5 years after completion, or abandoned during construction. If this situation continues unchecked, the basin may encounter a more serious disaster with quality of water resources, well interference and loss of space or reservation for future groundwater development.

Singh and Prakash (2004) integrated thematic maps through GIS for identification of groundwater potential zones. Kamaleshwar et al. (2000) integrated some physical parameters and terrain characteristics with GIS and remote sensing to extract groundwater prospect zone in Dala-Renukoot area of Uttar Pradesh, India. They arrived at five groundwater prospect categories. Kumar et al. (2010) has delineated groundwater potential zones using remote sensing and GIS techniques in Kurmapalli Vagu basin, India. They emphasized that systematic planning of groundwater development using modern techniques is essential for the proper utilization and management of this precious but shrinking natural resource. Similarly, they obtained five categories of groundwater potential zones ranging from very good to poor in the basin.

In this study, surface and borehole electrical resistivity and SP, and pumping data are integrated in GIS to map and explain the groundwater prospect zones of the basin. Low success rate of drilling productive wells is a common challenge in hard rock environment. The use of remote sensing with ground or well information is becoming effective method in improving success rate. Gezahegn (2012), integrated thematic layers generated from satellite images, existing maps and well data to delineate the groundwater potential zones of Upper Tumet catchment, Western Ethiopia**.** The resulting groundwater prospect map revealed that large part of the study area has poor groundwater potential which is in good agreement with field measurements.

Shahid and Kumar Nath (2008) observed that geophysical data help in locating the ground water potential in any hydrogeological setup. The property and thickness of various litho-units obtained from geophysical survey at different locations if integrated can yield a ground water potential model of higher reliability. Omosuyi (2010) conducted a geoelectric assessment of groundwater prospect and vulnerability of overburden aquifers at idanre, southwestern Nigeria and confirmed the suitability of the near surface aquifer for groundwater development.

Water table depth is an important map layer, parameter, and input variable for a wide variety of environmental models and groundwater development decision support tool. Water table maps are used to estimate ground water flow direction and velocity; vulnerability assessments or pollution transport. It is commonly used in environmental decision making such as locating landfills and wastewater disposal sites. The creation of water table maps is a well accepted practice in ground water investigations. Jasrotia and Singh (2005) used water table thematic layers and other parameters integrated through the DRASTIC model within a GIS environment to demarcate vulnerable zones of a watershed.

Vulnerability of water table aquifer south of the basin area

Figures 2 and 3 largely show contaminant transport to the southeast after (Nwachukwu et al. (2010c). The southward Otamiri River flow, and groundwater flow facilitates this transport (Figure 2). South-southeast tracking and capture zone of contaminants (Figure 3) suggest greater groundwater pollution. Groundwater flow, and contaminant transport is reduced in the south-end portion of the area with horizontal and vertical flows at the swamp (Figure 2b). There is indiscriminate dumping of solid waste, and disposal of urban sewage on farm land as fertilizer farm input. This habit increases bioavailability of trace metals and other contaminants in the southern portion of the basin. Shallow water table in the south west flank of the basin enhances contaminant transport and pollution of the water table \aquifer in the basin area. These conditions greatly endanger shallow water wells in the Imo River basin.

Using environmental impact models, Ibe et al. (2007) also reported that pollutants are transported southwards by surface water flow. According to them, the pollutants could easily migrate to the water table and immediately contaminate groundwater. Results of this study emphasize moderate to high vulnerability of the water table aquifer in the southern flank of the basin from where the shallow wells are recharged (Figure 4).

Khalek and Omran (2008) integrated remote sensing, geophysics and GIS to evaluate groundwater potentiality in Sohag region of Egypt. Three groundwater potentiality zones in the Quaternary aquifer of Sohag region were demarcated. This study has evidently demonstrated the capabilities of the integrated approach in delineation of the different ground- water potential zones. The approach can be used elsewhere with appropriate modifications for identifying candidate well locations and in creating a GIS-based hydrogeologic model of a selected area. Other scholars have integrated different other parameters to map groundwater potential zones successfully. Thus Mayilvagama et al. (2011) integrated thematic layers of lithology, geomorphology, drainage, soil, lineament, land use and surface water body to delineate groundwater potential zones in Thurinjapuram watershed. The result

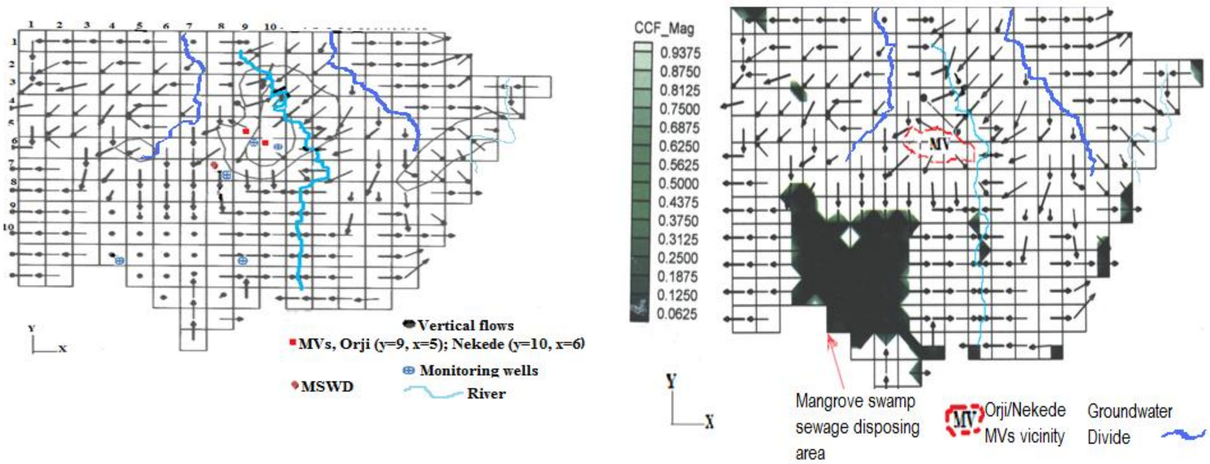

Figure 2. Groundwater flow model by MODFLOW model code, show direction of groundwater flow south of Imo River basin

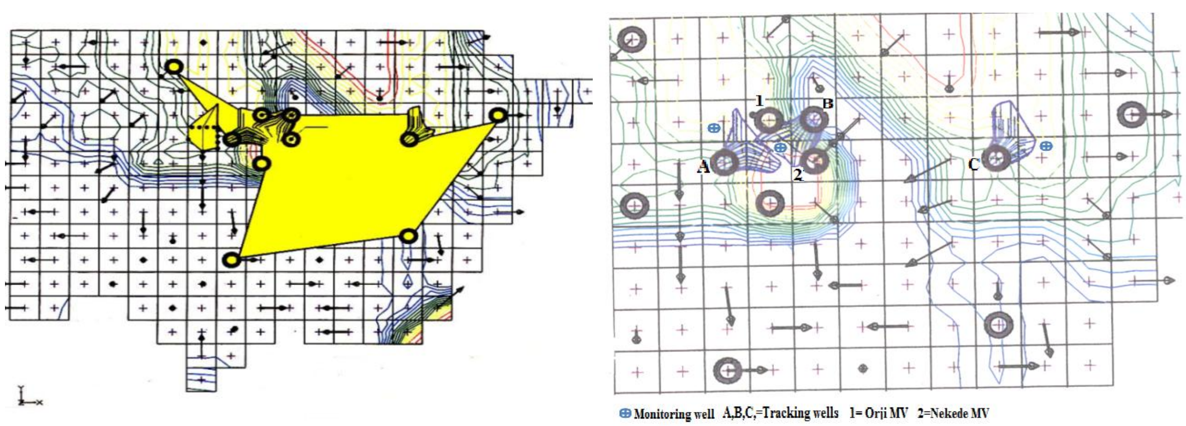

Figure 3. Faith and transport of contaminants obtained by MODPATH model code show (**a)** Particle capture zone (**b)** Particle tracking wells (ABC) south of Imo River basin.

showed three different groundwater potential zones namely 'good', 'moderate' and 'poor'.

MATERIALS AND METHODS

A total of 110 vertical electrical soundings (VES) data at two per county area, 50 geo-electrical down hole litho-logs, and 44 pumping test data were integrated in this study. VES and well-log data were provided by GEOPROBE Int'l Consultants Ltd Owerri, being data collected between 2000 and 2008. Status of the wells, yield and other important information were obtained from Imo State Water Development Agency (IWADA), Anambra-Imo River Basin and Rural Development Authority, Abia State Water Corporation, UNICEF, and some private individuals. The 110 VES were conducted using Allied Omega resistivity meter and Abem Terrameter (SAS 1000). The well log data was collected with Kerk Borehole Resistivity meter, Abem Terrameter and Scintrex instruments. These down hole loggers were used to measure apparent resistivity and the natural self-potential (SP). VES is the determination of vertical variation of resistivity through earth material, and is very reliable for groundwater exploration particularly in moderate terrain with less subsurface complexity as in the Imo River basin. VES field technique was based on the Schlumberger array conducted under good weather conditions. Readers may consult Telford, et al. (1990), Dobrin and Savit (1988), Reynolds (1997), USDOT (2004), and Kearey et al. (2002). These scholars have discussed the applications of electrical resistivity method in groundwater exploration and mapping in favour of vertical electric sounding (VES) by Schlumberger array.

Applicable GIS layers

A total of 44 reference wells, one in each county area were investigated. Location coordinate of each of the reference wells were measured with a geographic positioning system (GPS). The selected wells are those found within or near each county headquarter. Measured coordinates in degrees, minutes and

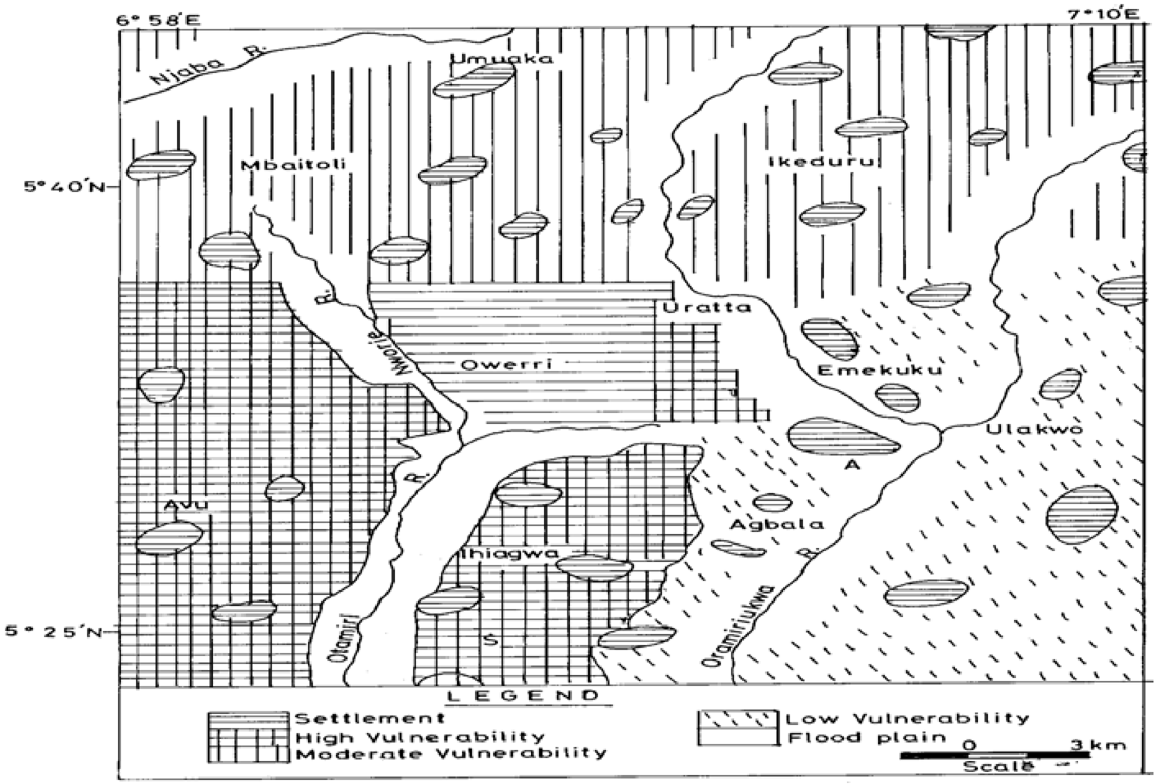

Figure 4. Soil and water vulnerability map of the study area produced by Ibe et al. (2007)

seconds (DMS) were converted to digital degree (DD) in excel sheet by the formula: (degrees) + (min/60) + (s/3600) = digital degrees.

The resultant decimal degrees as shown in Table 1 were applied to ArcMap version 9.3, so each reference well could display its ID, and other attributes. The following GIS layer maps were made: C*ounty areas, Mean Resistivity, Mean Thickness, Water table,* and *Groundwater Prospect.* The resultant groundwater prospect area map was compared and correlated with existing geologic map of the basin, to establish three groundwater prospect zones in the basin.

RESULTS AND DISCUSSION

Data analysis presented in Table 1 is described as the project data sheet. Water table (WT) and well depth (WD) are based on acceptable average values across each county. The stated lithology is for the prospective aquifer thickness (T) and average aquifer resistivity also refer to the prospective aquifer to the well depth (WD). The prospective well depth is found as the economic depth of standard water well for each county. Coordinates are shown in digital degree, as converted from degree, minutes and seconds and followed by the expected yield.

The 44 county area map of the Imo River basin (Figure 5) was obtained by merging Imo and Abia States local government maps over a digitized coordinate grid with geometric correction produced as GIS map 1. Average aquifer resistivity based on the 110 VES with at least two in each county as shown in Table 1 was contoured to produce the GIS resistivity map (Figure 6). The map indicates areas where the prospective aquifers have equal to similar resistivity, which is expected to relate to hydraulic conductivity of the aquifer. Previous studies by Ekwe et al. (2006), Ungemach et al. (1969) and Kelly (1977) have shown that electrical soundings can be used to estimate aquifer transmissivity and hydraulic conductivity, and that both possess empirical relationship.

Average aquifer thickness derived from the 110 VES and the 50 well-log data constituted the thickness map (Figure 7). The average thickness values were used to construct an isopach contour of the basin, and the corresponding GIS thematic map was made. The map indicates areas where the prospective aquifers have equal to similar thickness, which relates to the expected depth of standard water well in the affected area of the basin. Thematic maps (Figures 6, 7, 8 and 9) are only preliminary guiding tools to water well development stakeholders. They do not in any way eliminate the mandatory site specific groundwater pre-drilling and down-hole geophysical studies for water well development in the basin.

Average of water table depths obtained in each of the reference wells were considered as average depth to water. The average values were used to construct a water

Table 1. Project data analysis.

ID	County	WT	WD	T	Res	Lithology	x	y	Yield
21	Aboh Mbaise	200	350	150	1870	Sandstone	5.451111	7.233333	M-H
14	Ahiazu Mbaise	220	350	130	2020	Sandstone	5.751111	7.384166	M-H
20	Ezinihite	200	360	160	1960	Sandstone	5.466389	7.325111	M-H
7	Ihite Uboma	300	400	100	2200	Sandstone	5.511111	7.166666	M-H
8	Ehime Mbano	240	350	110	2280	Shaly-Sst	5.483056	7.551111	M-H
18	Ideato North	260	400	140	2210	Shaly-Sst	5.773611	7.158055	L-M
10	Ideato South	300	450	150	3270	Shaly-Sst	5.883333	7.133333	L-M
16	Ikeduru	240	350	110	2900	Sandstone	5.566667	7.100001	M-H
15	Isiala Mbano	280	400	120	2150	Sandstone	5.218889	6.917777	L-M
2	Isu	240	360	120	1620	Shaly-sand	5.796389	7.038888	M
17	Mbaitoli	200	340	140	2780	Sandstone	5.583333	7.050001	M-H
13	Njaba	290	400	110	2390	Sandstone	5.703333	6.770555	M-H
36	Ngor-Okpala	130	300	170	1308	Sst/G bed	5.800833	7.058333	P
3	Nkwerre	210	350	140	2640	Sandstone	5.750001	7.116666	L-M
5	Nwangele	300	380	80	1420	Shale top	5.797222	7.038888	L-M
19	Obowo	240	360	120	1790	Fractured	5.100001	7.092501	M-H
33	Oguta	80	240	160	1330	Sandstone	5.711667	6.809444	P
35	Ohaji/Egbema	120	370	150	1210	Sand/G bed	5.800833	7.916666	P
27	Okigwe	260	400	140	2090	Sand/G bed	5.483056	7.550001	L-M
9	Onuimo	230	350	120	3010	Shale/Sst	5.816667	7.200001	L-M
4	Oru East	280	380	100	1872	Sandstone	5.796389	7.038888	M
6	Oru West	260	380	120	3060	Mixed sand	5.711667	6.809444	M-H
11	Orlu	280	420	140	2940	Sand/G bed	5.783333	7.033333	M-H
12	Orsu	300	450	150	2090	Sandstone	5.816667	6.933333	M-H
1	Owerri Urban	100	280	180	980	Mixed sand	5.485001	7.035001	P
22	Owerri North	160	300	140	911	Sand/G bed	5.801389	7.051388	P
34	Owerri West	90	280	190	850	Sand	5.504167	7.021666	P
38	Aba North	120	360	240	1242	Sand	5.333333	7.316666	P
40	Aba South	100	300	200	1109	Sand	5.100001	7.350001	P
32	Arochukwu	240	320	80	3020	Shaly-Sst	5.416667	7.500001	L-D
30	Bende	230	320	90	3500	Shaly-sand	5.566667	7.633333	M
26	Ikwuano	200	320	120	3280	Sandstone	5.433333	7.566666	M
25	Isiala Ngwa N	130	300	170	1210	Sand	5.116667	7.366666	P
37	Isiala Ngwa S	100	300	200	1287	Sand	5.185278	7.601944	P
29	Isiukwuato	250	360	110	2100	Sandstone	5.533333	7.483333	L-M
39	Obi Ngwa	120	320	200	1250	Sand	5.149722	7.330277	P
31	Ohafia	180	280	100	3050	Sandy-Shale	5.616667	7.833333	L-D
41	Osisioma Ngwa	130	340	210	1150	Sand	5.416667	7.500001	H H
42	Ugwunabo	100	300	200	962	Sand	5.185278	7.601944	P
44	Ukwa East	120	320	200	850	Sand	5.116667	7.366666	P
43	Ukwa West	100	320	220	840	Sand	5.104722	7.142501	P
23	Umuahia North	300	400	100	3280	Sandy-shale	5.533333	7.483333	L-M
24	Umuahia South	180	300	120	1720	Sand	5.508056	7.481666	M-H
28	Umu Nneochi	250	400	150	2270	Sandstone	5.104722	7.142501	L-M

*WT = Average water table, WD = Recommended well depth, Res = Mean resistivity value. P = Prolific), M-H = Medium to high yield, L-M = Low to medium yield, L-D = Low yield to dry well. G bed = Gravel bed, Sst = Sandstone and T = Thickness of prospective horizon.

table contour from which a GIS thematic map layer showing six water table depth classifications in the basin area was produced (Figure 8). All the GIS layers were overlaid, with different symbols assigned to the identified features in each layer. The resultant composite coverage was classified into five groundwater prospect zones (Figure 9).

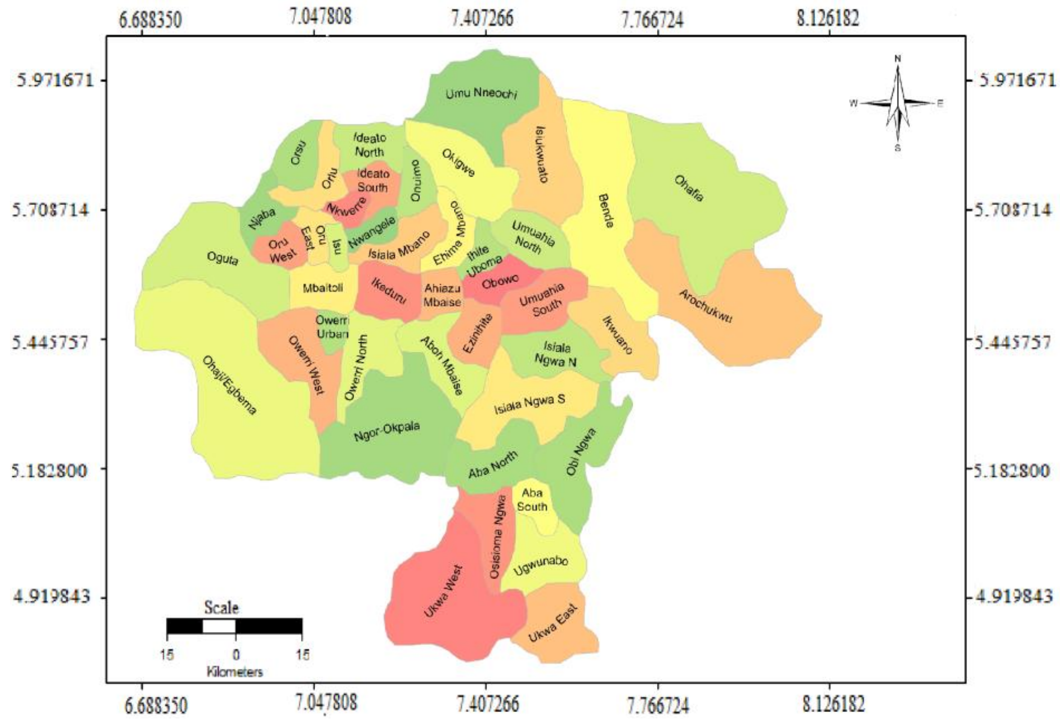

Figure 5. Thematic map of the Imo River basin showing layer of the 44 county areas.

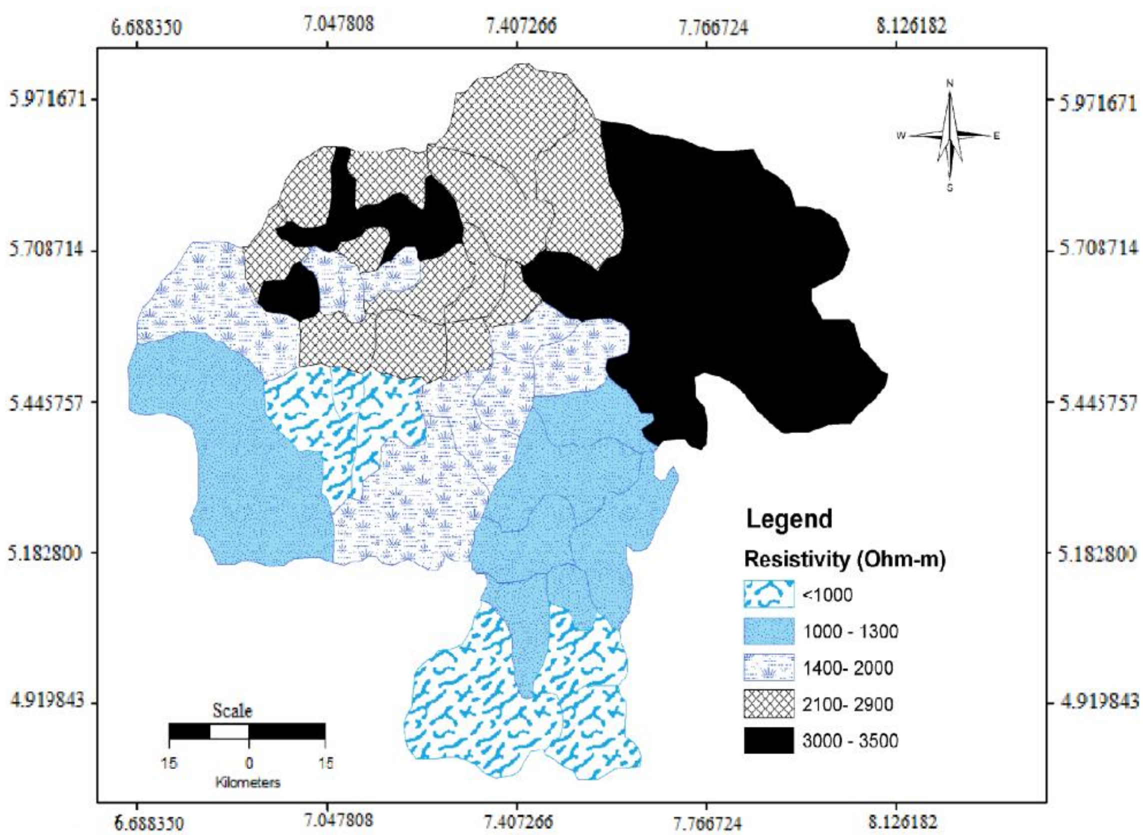

Figure 6. Thematic map of the Imo River basin showing layer of average resistivity

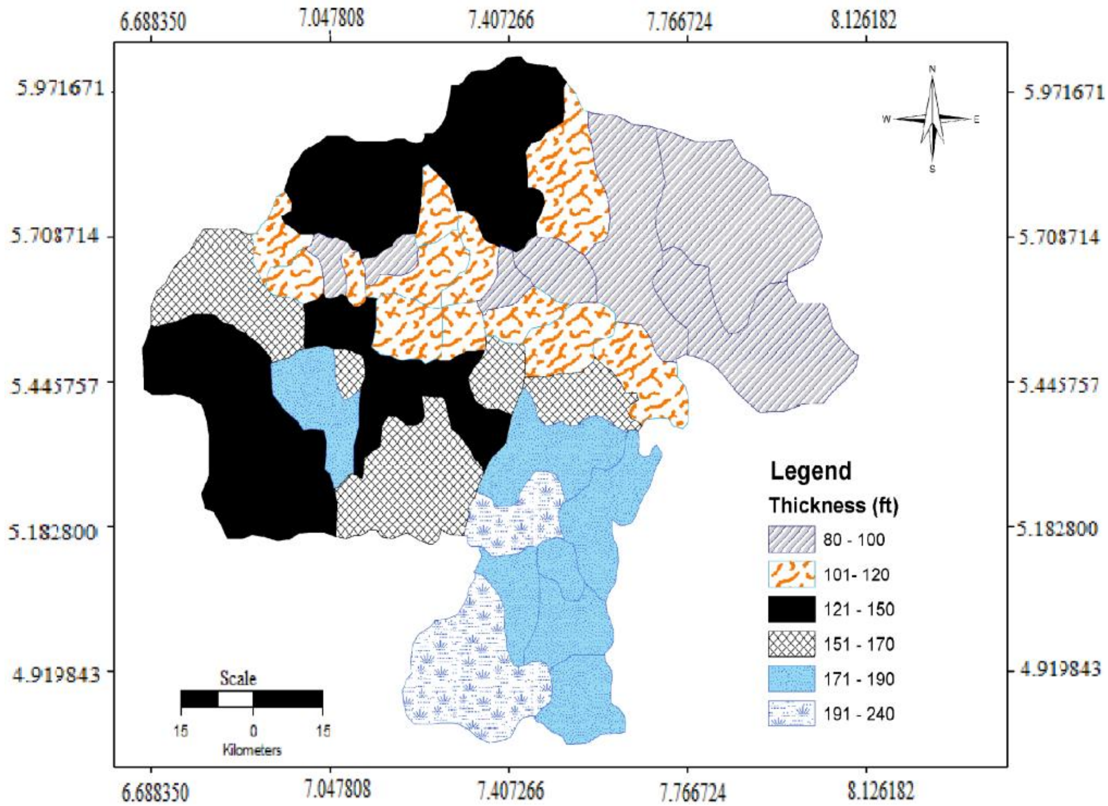

Figure 7. Thematic map of I mo River basin showing layer of average aquifer thickness.

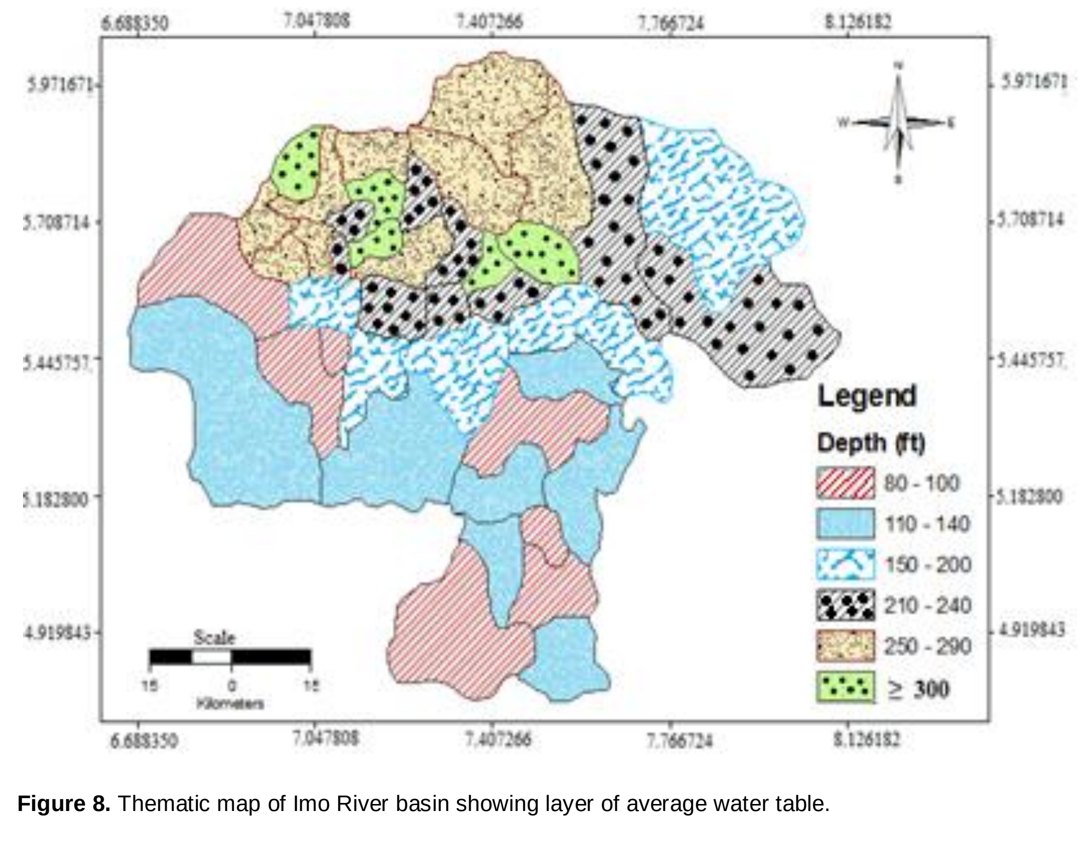

Figure 8. Thematic map of Imo River basin showing layer of average water table.

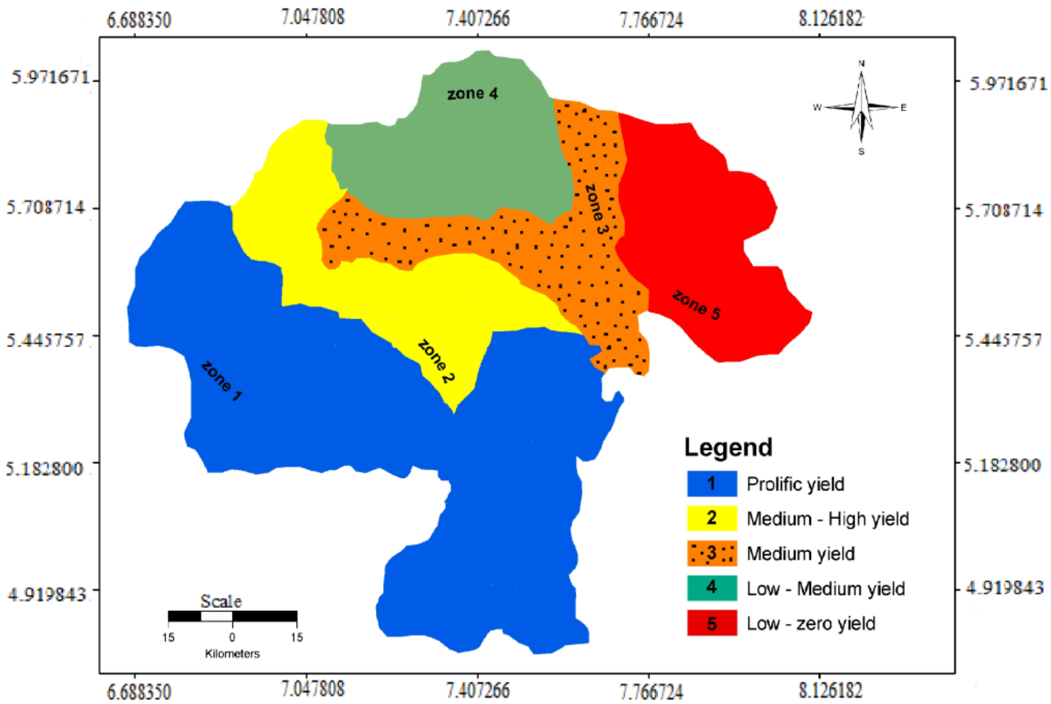

Figure 9. Groundwater prospect Model in the Imo River basin.

This output map is correlated with the groundwater data collected in the field, and represents the groundwater prospect map of the basin. This map integrates the analytical results of pumping test data and well status information in five groundwater areas. Area 1 is characterized by prolific yield; ≥ 25 m^3/h. Area 2 is medium to high yield (M-H), with medium yield being ≥ 11 m^3/h, and area 3 is the medium yield areas. Area 4 is low to medium (L-M), with low yield as ≤ 10 m3/h, whereas Area 5 is the area characterized by very poor to zero yield. This area accounts for a good number of dry or abortive wells. Ganapuram et al. (2008) used a similar classification to assess the groundwater potentials of the Musi basin, and qualitatively they classified the basin into very good, good, moderate, poor and nil based on hydro-geomorphologic conditions.

Area 2 (Medium-high yield) included parts of 6, 7, 8, 15, and 19, *Area 3* (Medium yield) include the northern parts of 3, 5, 6, 7, 8, 15, 19, 23 and 24, while *Area 4* (Low-medium yield) included the southern parts of 3, 5, 7, 8 and 15 county areas. This recommendation is a general guide, which does not eliminate site specific variations as may be applicable. Again, they do not in any way eliminate the mandatory site specific groundwater pre-drilling and down-hole geophysical studies for water well development in the basin.

Groundwater prospect increases from the north to the south of the basin following the characteristic decrease in shaliness from the north to the coastal plain sand of the Benin Formation in the south. However, the proliferation of shallow private/commercial substandard water wells and the number of abortive, abandoned, and non-functional wells threatens sustainability of groundwater in the basin.

Information on standard water well development of all the 44 local governments shown in the GIS map contain attribute data and ID as contained in Table 1. Attribute data for each local government water well can be assessed by clicking on the particular local government area. A GIS map of this nature is very necessary. It will solve the problem of water well statistics, and remain an essential tool of government for decision making in water resource management. It will serve as a government working tool in the award of contracts for public water wells, and in post construction maintenance of the wells.

Justifying the GIS groundwater prospect model

The existing regional geology map of the basin (Figure 1c) is used to justify the GIS groundwater prospect model of this study. There is significant correlation between the regional geology and the groundwater prospect model as illustrated in Figure 10. Three groundwater prospect zones have been defined out of the five groundwater *Areas* classified earlier, based on the correlation. This correlation could be used to adjust or review boundary of geologic units in future studies. Overlapping boundaries

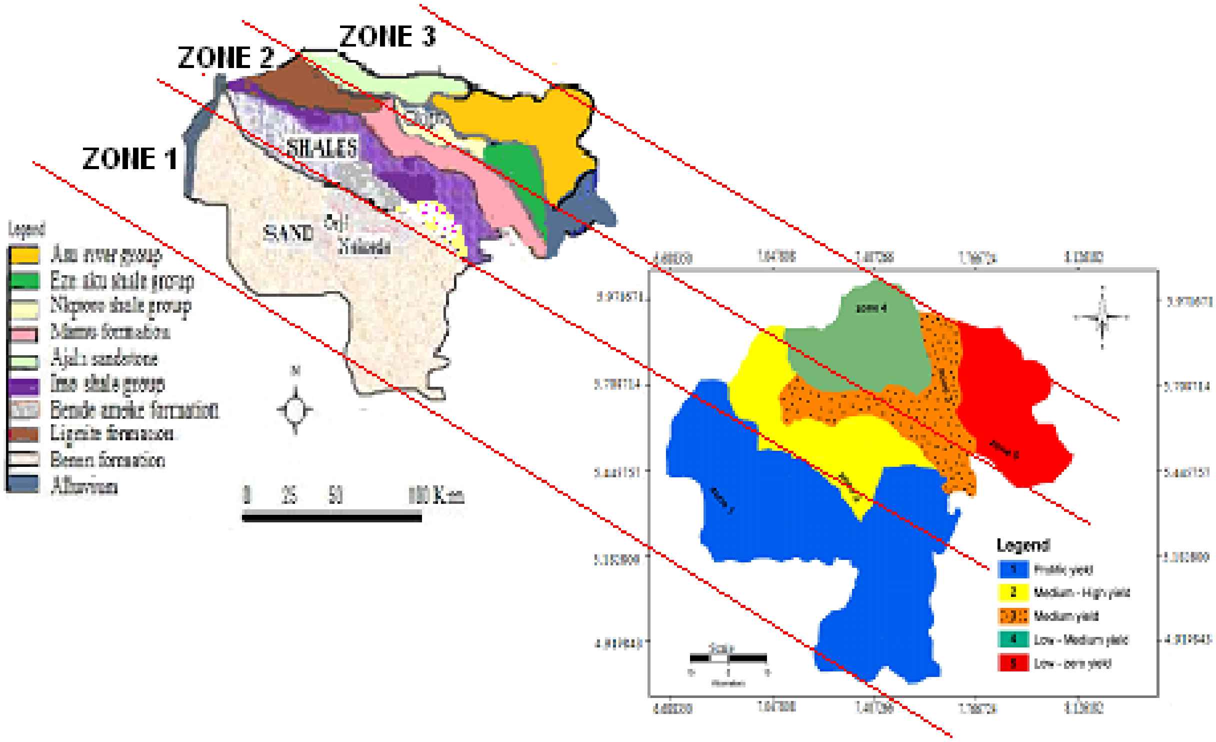

Figure 10. Correlation of Regional geology with the groundwater prospect model.

in the correlation can be described as transition areas. Zone 1, characterized by prolific yield consists of sand belonging to the Benin Formation. Zone two of medium to prolific yield is sandy with mixed shale, and the shaliness increasing to the north. Zone three consists predominantly of shale with minor sand units. This zone is characterized by poor to medium yield. This correlation has further confirmed that groundwater prospect is controlled by subsurface geology. It implies that spatial geophysics and geologic data integrated to GIS can provide comparable information about geology and hydrogeology of a region.

Other problems of groundwater development and supply in the basin

The lack of public water supply notwithstanding, private wells cannot replace public wells in communities. Less than three percent “privileged citizens” supposed to facilitate the maintenance of public water wells have their private shallow wells. They are therefore unconcerned with presence or functionality of public wells in their communities. As a result, most public wells are neglected; non functional, contributing to the inefficiency of public water supply, and low impact of government efforts towards public water supply in the area.

A summary of other major factors militating against sustainable groundwater development in the basin is as follows:

1) Poor environmental quality causing groundwater pollution.
2) Improper or partial distribution of public wells due to lack of easily retrievable information on existing wells in the region, and favouritisms. Often a community may have two or more public wells whereas the next community does not have one.
3) Poor maintenance and often sabotage in the development and operational processes of public wells. Fund budgeted for water well development and maintenance may be diverted, resulting to the use of inferior materials and no proper supervision during the well construction.
4) Several non functional and abortive wells are not properly closed or sealed from interference; some become waste disposal pits. Such wells are transport pathways of contaminants to groundwater.

RECOMMENDATIONS

Water well partnership

Surface water development is thus recommended in the difficult, low to zero yield areas of zones 4 and 5, against the prevailing groundwater development. We are recommending two types of water well partnerships as innovative strategy to improve water supply, improve water quality, reduce incidents of well failure, and uphold a sustainable groundwater development system in the Imo River basin. First is the government-private partnership: In this case, government wells could be privatized even at immediately after completion to citizens under a mutual agreement. The partner citizens will be responsible to the day to day operation, distribution and management of the wells to the benefits of the host communities. Second is a private-private partnership: Here two or more individuals and organizations that have plans to develop their private wells could combine their resources. By so doing, rather than the proliferation of shallow substandard private/commercial wells, the partners now could develop standard water wells to serve their respective households and neighbourhood. Government may provide incentives to support water well partnerships.

Conclusion

Groundwater prospect GIS model of a river basin is a vital tool to sustainable development of groundwater resource. Comparing groundwater prospect GIS model with the basin's geology map provides better judgement on how to manage and conserve groundwater in a basin. Result of this study has confirmed that surface water development is most appropriate in the difficult, low to zero yield areas of zones 4 and 5, as, against groundwater development.

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