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GIS-Based Spatial Analysis Accurately Predicts Alluvial Well Depletion and Effectively Establishes Relationship between Aquifer Parameters

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Abstract: Groundwater extraction from wells located near streams can decrease stream flow. This is commonly referred to as 'alluvial well depletion'. Several analytical explanations were established for alluvial well depletion that differs in their mathematical intricacy. However, to date, only a few stream aquifer analysis tests have been documented in the literatures. To successfully quantify the level of stream aquifer interaction during pumping, it is required that the stream bed hydraulic conductivity is estimated. In this study, over 1000 borehole data were employed in GIS-based spatial analysis and was found to accurately predicts alluvial well depletion. In addition, spatial relationship between aquifer parameters were effectively established among some parameters such as: conductivity, topography, yield, soil type, recharge and aquifer media. It was established that the area with highest conductivity is generally characterised by the alluvial well depletion effect and groundwater flow pattern is not only controlled by the structure of the water table but also by the distribution of hydraulic conductivity. In addition, no association was found to exist between steep slope and the conductivity as very strong relationship ensued between areas with high recharge and soil media. Relatively high association was evident between aquifer media, recharge and soil media.These, apart from validating the quality of data used, have also endorsed several theoretical assertions.

Key words: Kano · Stream-aquifer analysis · Alluvial well depletion · Transmissivity · Conductivity · Specific Capacity · Recharge

INTRODUCTION

Groundwater extraction from wells located near streams can decrease stream flow. This is commonly referred to as 'alluvial well depletion'. Several analytical explanations were established for alluvial well depletion that differs in their mathematical intricacy. However, to date, only a few stream aquifer analysis tests have been documented in the literatures which compare field measured streambed parameters [1].

To successfully quantify the level of stream aquifer interaction during pumping, it is required that the stream bed hydraulic conductivity is estimated [2]. The bigger scale hydrologic interchange between groundwater and surface water on a land is controlled by (1) the distribution and magnitude of hydraulic conductivities (2) the relation of stream stage to the adjacent groundwater level and (3) the geometry and position of the stream channel within the alluvial plain [3]. The direction of the exchange processes varies with hydraulic head, whereas flow (volume/unit time) depends on sediment hydraulic conductivity [2].

Groundwater flow pattern is not only controlled by the structure of the water table, but also the distribution of hydraulic conductivity in the rocks. In addition to topographic and geologic effects, groundwater flow is affected by climate (precipitation being the source of recharge) [2]. Mixed-flow systems occur where the

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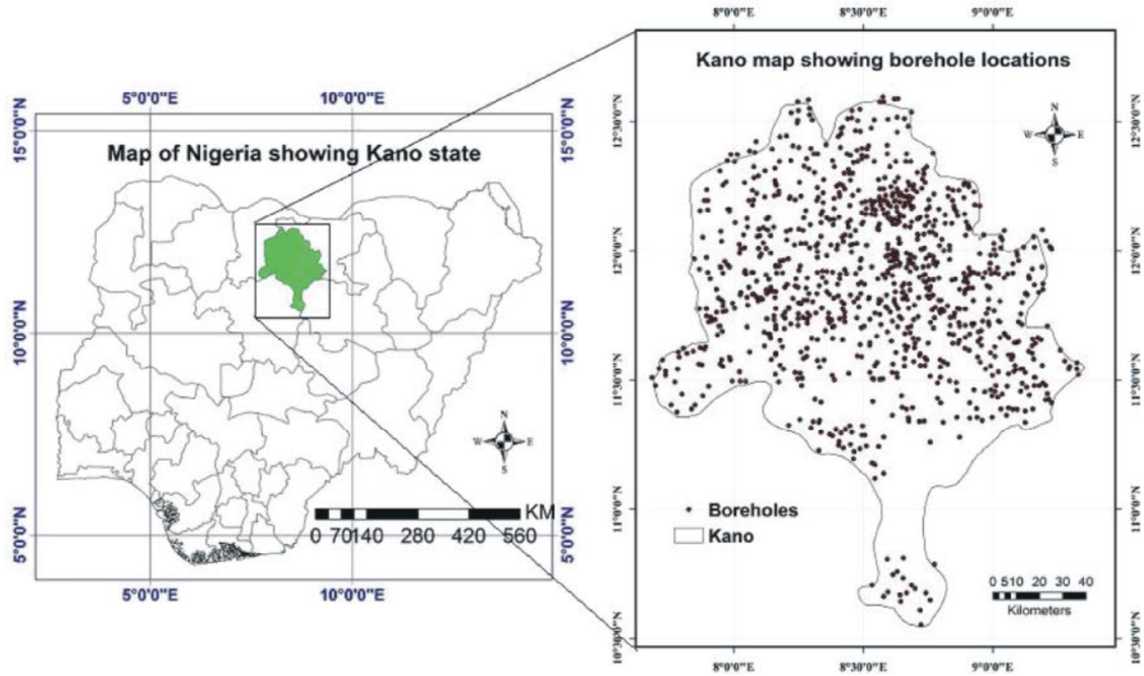

Fig. 1: Study area showing location of boreholes used in this study

longitudinal valley gradient and channel slope are virtually the same and where the lateral valley slope is negligible [2]. Among the major low yield in wells is the low hydraulic conductivity of the formation [4].

According to [5], well yield is controlled by the state of the hydro-mechanical properties of the nearby surrounding area of the borehole. Specific capacity, transmissivity and hydraulic conductivity are also associated with well yields in bedrock aquifers. Therefore, the well yield should be considered an acceptable and reliable statistical test validator for a comparative study of the hydraulic systems in different hydrogeological locations [5]. Fractures and faults zones are areas with high permeability.They also have preferential flow with a conduitbehavior [11-14].

The downward movement of water occurring from precipitation or snowmelt through the soil into the underlying rocks is what constitutes groundwater [6]. Borehole drillers usually provide vital information regarding recovery tests. However, careful measurement of this information may be used in groundwater hydraulics to ascertain reliable borehole efficiency [7]. Understanding the interface between groundwater and surface water is fundamental in the management of water resources. The management of the groundwater requires the knowledge of groundwater drainage basin boundaries and groundwater recharge rates. The groundwater drainage basin boundaries are commonly assumed to be the watershed boundaries defined by surface topography [8, 9]. In Nigeria, the absence of proper hydrogeological base maps, poor knowledge of the geology, shortage of infrastructural facilities and lack of a working legislature have tormented the practice of hydrogeology. These have led to the problems in exploration, exploitation, operation, control and management of the abundant groundwater resources [10].

Study Area: Kano (Fig. 1) is one of the 36 states of Nigeria. Located in the Sudan Savannah, between latitude 10° 23’ 40’’, 12°34’ 24’’ North, 7° 41’ 15’’, 9° 21’ 21’’ East. The total area cover of Kano is 20,131 km^2.The climate of Kano is seasonally arid. Rain falls between May and October with a peak in August and the mean annual rainfall is between 635 to 1500 mm. The aquifers of the Kano basement complex rocks are regolith and fractures in the fresh bedrock interconnected at depth.

MATERIALS AND METHODS

Hydrogeological and Meteorological Data: This study draws upon 1000 wells completions final reports [39].Thedata was then analyzed in ArcGIS 10.1 and the resulting wells location is as presented in Fig. 1. Furthermore, this study adopted ‘Inverse Distance Weighted’ (IDW) interpolation technique. Being the best technique for representing groundwater conditions

Table 1: Data Sources

Data type	Sources
Well Log Data (Geographical location, Well depth, Static water level, Drawdown and soil type)	Kano Agricultural and Rural Development Authority (KNARDA (1990) [39]
Hydrological Data (precipitation)	Kano state Water Board (KSWB. Technical Services Division)
Kano Administrative Map	Global Administrative Areas GADM
Digital Elevation Model (DEM) (watershed delineation)	A Shuttle Radar Topography Mission (SRTM) digital elevation model (DEM) having 30m resolution obtained from the United States Geological Survey (USGS)

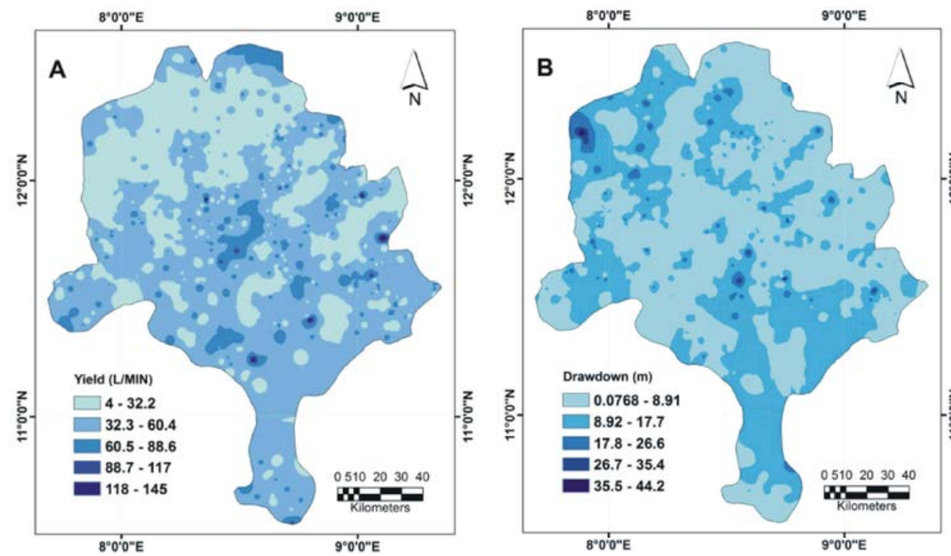

Fig. 2: (A) Borehole yield and (B) drawdown maps

[15-19]. The precipitation data spanning 37 years obtained from nine (9) meteorological stations spread over the entire study area were used in this study. The location of each station was obtained using a geographical positioning system (GPS).

Topographic Data: A Shuttle Radar Topography Mission (SRTM) digital elevation model (DEM) having 30m resolution obtained from the United States Geological Survey, USGS was used in the watershed delineation. One of the encouraging scientific tools for assessment and management of water resources are the surface hydrological indicators. Drainage analyzes are essential for the choice of water recharge site, watershed modeling, runoff modeling, watershed delineation, potential groundwater mapping and geotechnical examination [20].

Specific Capacity: The measure of the rate at which water may be pumped to attain certain 'Drawdown' (S) in a well is referred to as Specific capacity (S_c). It is the ratio of pumping rate to drawdown in a well and usually correlates with hydraulic flow properties given by Eq 1. [21].

$$S_c = {}^{Q}\!/_{S} \tag{1}$$

where S_c is the specific capacity, Q is the discharge or yield of well and S is the drawdown.

In this study, the S_c was calculated spatially in ArcMap from the yield and drawdown data provided for each well. The maps obtained for the yield and drawdown is respectively shown in Fig. 2 (A and B).

When the ratio was taken using 'Map Algebra' tool, a thematic map of specific capacity over the entire study area was realized as shown in Fig. 3.

Transmissivity: Transmissivity is a vital aquifer hydraulic property. It enables us to assess the likelihood of groundwater abstraction thereby drawing vital inferences in hydrogeological studies. Hydrogeological maps of transmissivity are usually desirable because they provide a basis for impending groundwater exploration, abstraction, protection and development [22].

With each pixel representing a well after interpolation in an ArcGIS environment, the Transmissivity of wells within the study area based on the Eq 2. given by [23] being a conductivity equation for the assessment of

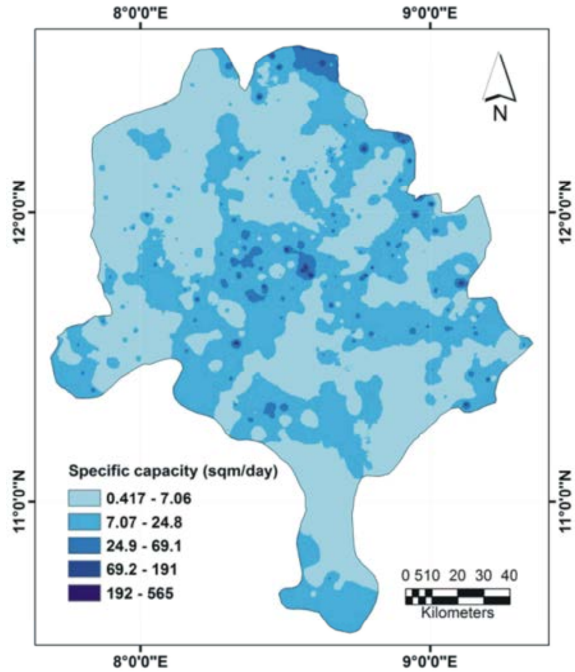

Fig. 3: Spatial map of specific capacity

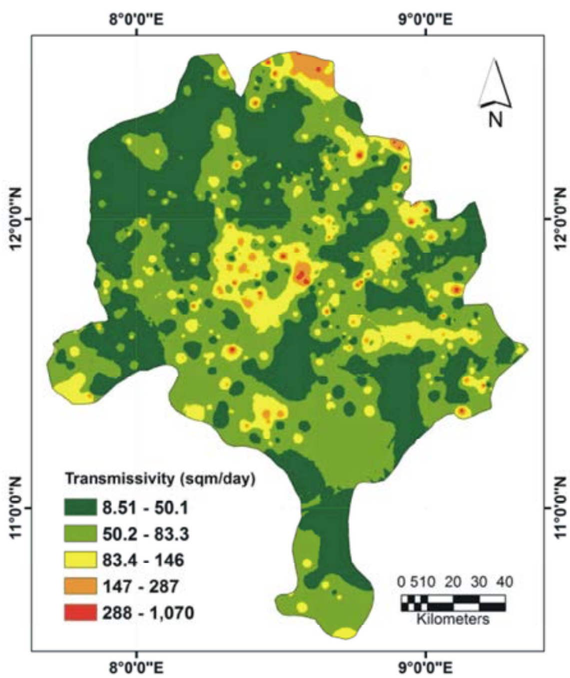

Fig. 4: Transmissivity map of Kano

transmissivity from specific capacity in a heterogeneous alluvial aquifer. The adoption of the equation was after the careful definition of the study area vadose zone.

$$T = C(S_C)^{0.67} \tag{2}$$

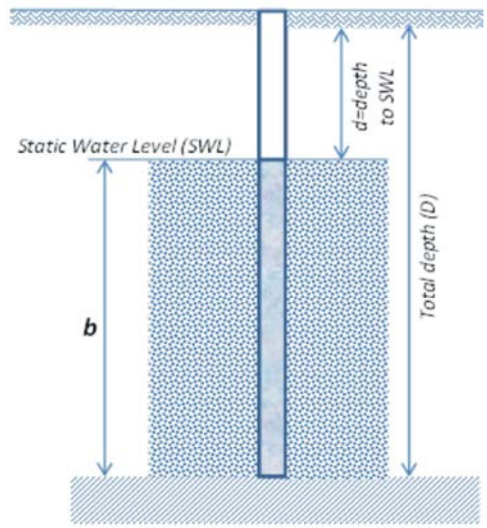

Fig. 5: Diagram illustrating saturated depth

where C =15.3 obtained from table provided by [23] for values in m^2/day

Substituting C in Eq. 3, the equation is rewriten as:

$$T = 15.3(S_C)^{0.67} \tag{3}$$

Solving Eq. 3 spatially using map algebra, the resulting transmissivity map of the entire study area is shown in Fig. 4.

Hydraulic Conductivity: The capacity of an aquifer to transmit water is referred to as conductivity [24, 25]. The conductivity value of soils may differ greatly from one place to another and will similarly vary spatially (different depths). Not only can different soil layers have different hydraulic conductivities, but even within a soil layer, the hydraulic conductivity can vary [26]. Transmissivity (T) is the product of aquifer thickness (saturated) (b) and hydraulic conductivity (K) (Eq.4)

$$T = Kb \tag{4}$$

where T is transmissivity, K is hydraulic conductivity and b is the saturated thickness of aquifer.

From Eq. 4, therefore, hydraulic conductivity (K) can be obtained as using Eq. 5.

$$K = T/b \tag{5}$$

The saturated thickness is obtained by subtracting static water level (Fig. 6B) from the total well depth (Fig. 6A) based on Eq.6; as illustrated in Fig. 5.

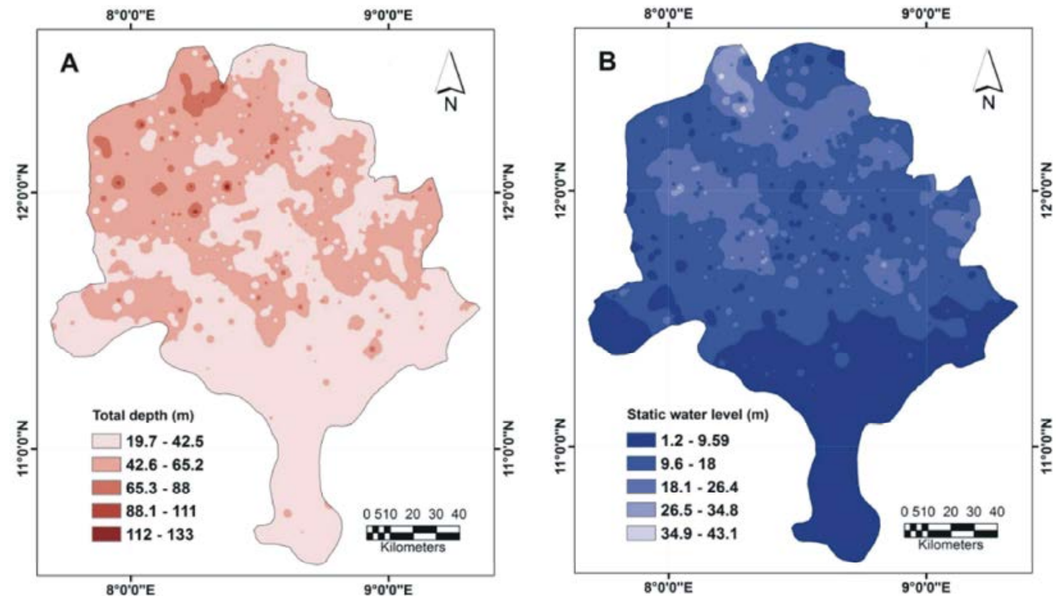

Fig. 6: Total and static water depths map

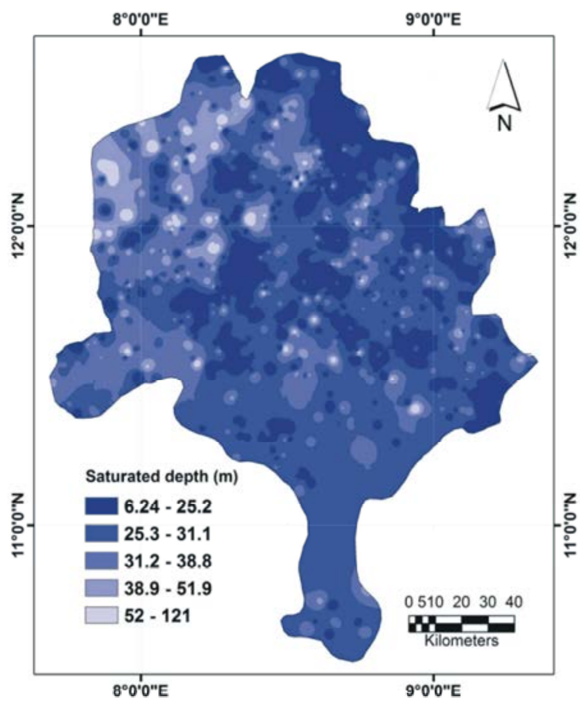

Fig. 7: Saturated depth map of Kano

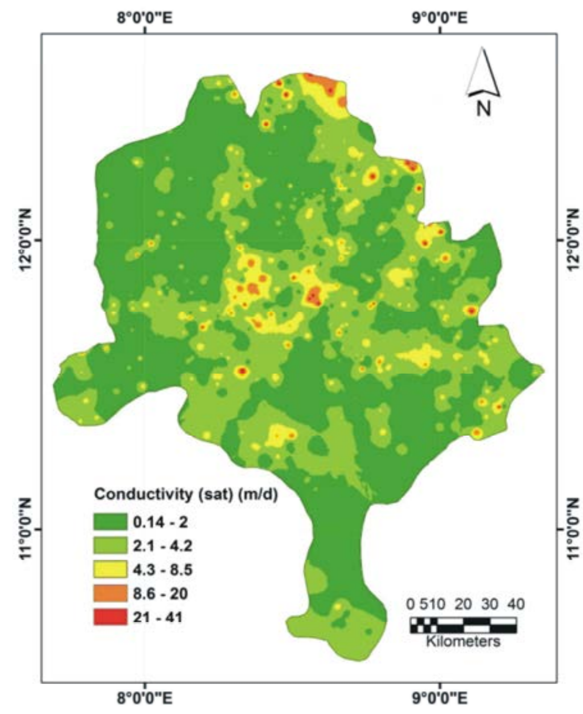

Fig. 8: hydraulic conductivity map of Kano

$$b = D - d \tag{6}$$

where b is the saturated depth, D is the total depth and d is the depth to static water level.

When Eq. 6 was spatially evaluated, the saturated depth map of the watershed was obtained as shown in Fig. 7.

Finally, the hydraulic conductivity map (Fig. 8) of the entire study area was obtained using map algebra based on Eq.5.

Recharge: Recharge is 'the entry into the saturated zone, water made available at the water-table surface, together with the associated flow away from the water table within

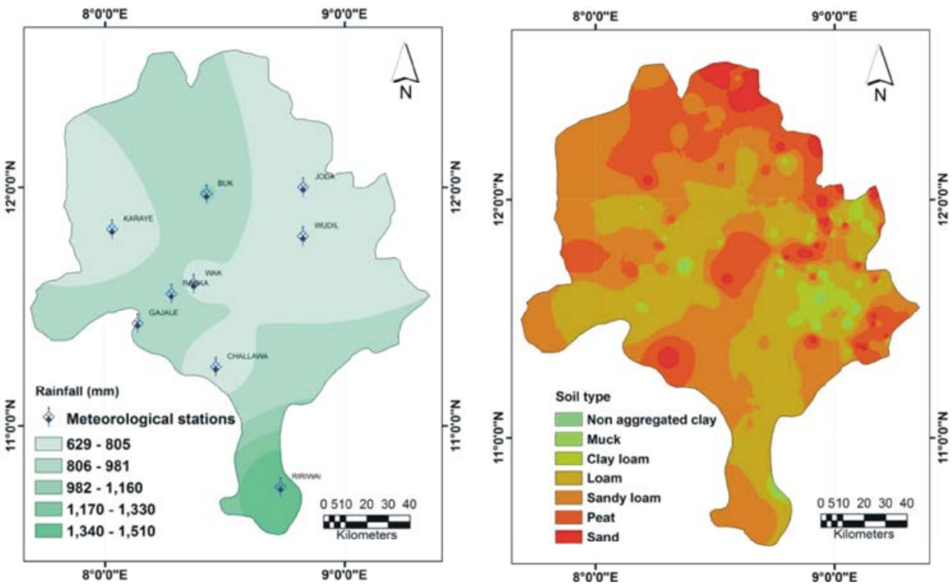

Fig. 9: (A) Rainfall pattern and (B) soil type

the saturated zone' [27]. Groundwater recharge is an essential component in the water balance of any watershed. However, because of the difficulty of its direct measurement, various methods have been employed for the recharge assessment [28, 29]. The best recharge estimate by hydrologists, is usually by employing methods that are reasonably straightforward in their application and require only commonly available hydrologic data [30-32]. For proper management of groundwater resources, accurate estimation of groundwater recharge is exceptionally central [33, 36, 37]. Particularly in arid and semi-arid parts of Africa where the main water source is groundwater, which prospectively makes the region liable to depletion based on the impending climate changes [36].

In this study, an empirical method according to Williams and Kissel's equation (Eq. 7) was adopted for the evaluation of the annual recharge. Same equation adopted in different groundwater pollution studies such as that by [33-35]. Eq.7a is applied when evaluating recharge for hydrologic soil, gravel and sand. Eq. 7b is applied for hydrologic soil sandy loam, peat and loamy sand.

$$PI = (P - 10.28)^2/(P + 15.43) \quad (7a)$$

$$PI = (P - 15.05)^2/(P + 22.57) \quad (7b)$$

where PI is the percolation index and P is the annual average rainfall.

In a view to obtaining a spatial distribution of rainfall over the study area, the mean annual precipitation values were interpolated using IDW technique. The map obtained is shown in Fig. 9 A. Furthermore, the soil map (Fig. 9B) was deduced from the borehole log data obtained from KNARDA. The soil map gives an idea of the appropriate equation suitable for particular zone.

Solving Eq.7 (a and b) as the case may be, based on the obtained maps shown in Fig. 9 using map algebra, the interpolated recharge value over the study areaare shown in Fig. 10.

Aquifer Assessment: The aquifer media for each well were categorised based on the well log information. In addition, the no/or poor yield zones were also utilised in the aquifer assessment in this research. The no/poor yield zones delineation is utilised as obtained in a study by [38].

Stream-Aquifer Analysis (SAA) Test: Since groundwater extraction from wells located near streams can decrease stream flow; which is commonly referred to as 'alluvial well depletion', it implies that the rate of conductivity is expected to be higher when a well is located near a river. However, to successfully quantify the level of stream aquifer interaction, it is required that the stream bed hydraulic conductivity is estimated. This is because one of the bigger scale hydrologic interchange between groundwater and surface water on a land is controlled by the distribution and magnitude of hydraulic

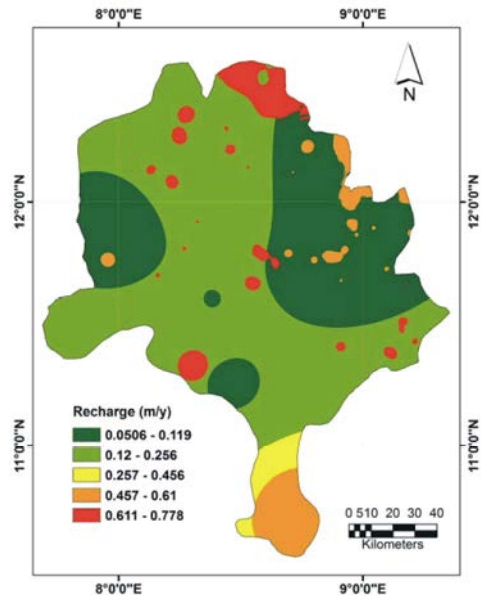

Fig. 10: Recharge map of Kano

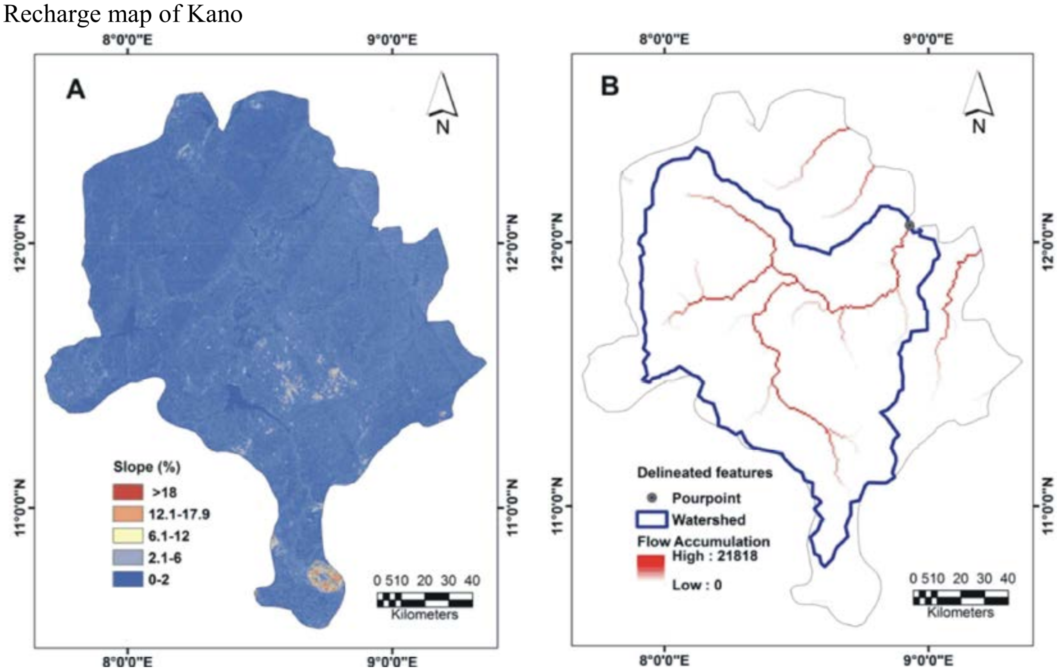

Fig. 11: (A) Slope and (B) delineated flow accumulation and watershed

conductivities, the relation of stream stage to the adjacent groundwater level and the geometry and position of the stream channel within the alluvial plain as stated by [3].

The steeper the angle of inclination of slope, the greater the runoff flow and the less the recharge ability of the aquifer. and vice-versa. In defining the topography of the study area, a Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) was used. A percentage slope from 0 - >18% was adopted as shown on Fig. 11A.

In a view to determine the spread and positions of streams within the study area, the DEM was used to delineate the watershed. In delineating the watershed, Spatial Analyst (hydrology tool) sets were employed. The steps involved are as follows: (1) Slight imperfections in the DEM surface raster data were removed using the 'Fill.' (2) A raster flow bearing from each cell was created using

'Flow Direction' tool. (3) A raster defining the accumulated flow into each cell was also generated using 'Flow Accumulation' tool. (4) Highest flow accumulation within cells was snapped using the 'Pour point'. (5) Finally, the watershed (contributing area above a set of cells in a raster) was delineated using the 'Watershed' tool. The resulting delineated watershed area is shown in Fig. 11B.

From the delineated feature, various stream-aquifer analyses (SAA) were performed vis-à-vis the hydraulic conductivity parameter; as relevant information was deduced therefrom.

DISCUSSION

The overall transmissivity of wells based on the two aquifer types that characterized the study area was found to have the minimum, maximum and mean value of 0.045, 1068.4 and 36.75m2/day respectively (Table 2). Hydrogeological maps of transmissivity will provide a basis for impending groundwater exploration, abstraction, protection and development of the study area..

When the saturated depth data was calculated and analyzed, the resulting map indicated that the minimum saturated depth is 6.24m, maximum is 121.49m and the mean depth is 29.70m. The deeper area is predominantly within the northwestern part, while the shallower is in the central part of the watershed.

The conductivity being the capacity of an aquifer to transmit water, however, indicated that the aquifer within the watershed has the minimum value of 0.00081m2/day, 63.52m2/day maximum while 1.35m2/day is the mean (Table 2).

According to the rainfall data obtained from the 9 meteorological stations across the entire state, the amount of rain that fall annually is 629mm minimum, 151mm maximum and the mean is 828mm. Upon the assessment of recharge rate over the area vis-a-vis the rainfall data, it was established that the minimum, maximum and mean annual recharge is 0.051, 0.61 and 0.15m/y respectively.

Stream-Aquifer Analysis (SAA) Test: From the literature it was established that groundwater extraction from wells located near streams can decrease stream flow; which is commonly referred to as 'alluvial well depletion' and to date, only a few SAA tests have been documented in the literatures which compare field measured streambed parameters. To successfully quantify the level of stream aquifer interaction it is essential that the stream bed hydraulic conductivity is assessed.

Stream, Conductivity and Topography Relationship: From Fig. 12, it is apparent that there is possibility of 'alluvial depletion' since the evaluated conductivity map indicated that the wells located near flow accumulation areas indicated higher conductivity rate. This apart from validating the data quality has also endorsed the theoretical assertion that decrease of stream flow (alluvial well depletion) is expected to be higher when a well is located near a river (i.e. where high rate of conductivity is anticipated). This has also confirmed the fact that groundwater flow pattern is not only controlled by the structure of the water table but also by the distribution of hydraulic conductivity.

Again, as affirmed in the literature, topography also affects the groundwater flow. This was found to be true as a test was conducted using different percentage slope (i.e. 12-18%). The relationships were determined between slope and various levels of conductivity. From Table 3, it can be concluded that there is virtually no connection between steep slope and conductivity in the study area as the level of 'No connection' between them was established to be from 99.66-100%.

Conductivity, Soil type, Recharge and Aquifer Media Relationship: Among the factors controlling conductivity is the geology of the area. In establishing the relationship between the geologic parameters and the conductivity, an average conductivity of the area (i.e. 2.3m/day) was utilised against the peak values of the parameter in comparison as shown in Fig.13. After the analysis it was found that the percentage relationship was between 45.21

Table 2: Summary of hydrogeological data of Kano, Nigeria

S/N	Parameter	Min	Max	Mean	SD
1	Yield (Q) (m^3/day)	4.00	145.00	38.67	14.22
2	Drawdown (S)(m)	0.08	44.23	8.56	3.67
3	Specific Capacity (S_c) (m^2/day)	0.42	565.33	8.43	8.76
4	Transmissivity (T) (m^2/day)	8.51	1068.40	60.26	32.32
5	Total Depth of (m)	19.7	133.49	43.24	8.97
6	Depth to Static water level (m)	1.20	43.15	13.54	5.58
7	Saturated Depth (b) (m)	6.24	121.49	29.68	7.00
8	Hydraulic Conductivity (Sat)(K_s)(m/day)	0.14	41.00	2.26	1.81
9	Rainfall (mm)	629.00	1,508.00	828.15	147.63
10	Recharge (m/year)	0.051	0.61	0.15	0.09

Min=minimum, Max=maximum, SD=standard deviation

Table 3: Conductivity-slope relationship

Conductivity (K) (m/day)	Percentage area cover (%)	Slope-conductivity relationship: Connection (%)	Slope-conductivity relationship: No connection (%)
2	46.28	0.34	99.66
2.3*	35.17	0.14	99.86
4.3	8.11	0.01	99.99
8.6	1.21	0	100

*Average for the entire study area

Table 4: Conductivity, soil type, recharge and aquifer media relationship

	Conductivity	Recharge	Soil media	Aquifer media
Conductivity	100			
Recharge	45.21	100		
Soil media	60.79	100	100	
Aquifer media	82.38	69.00	69.00	100

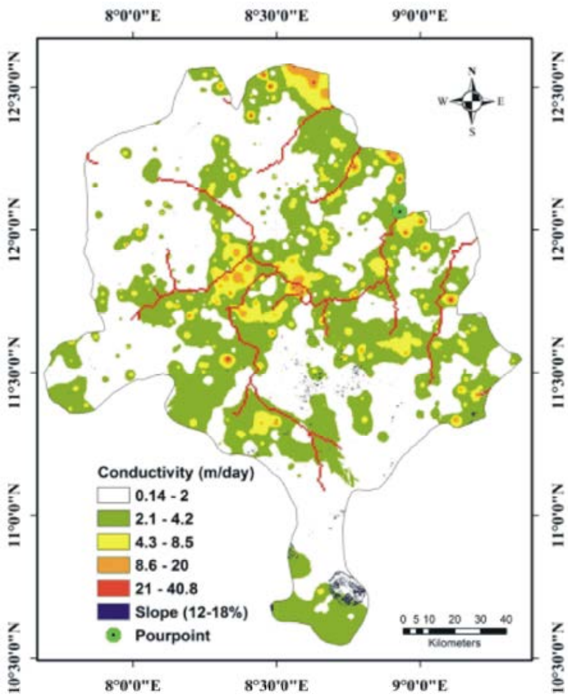

Fig. 12: Stream, conductivity and topography relationship

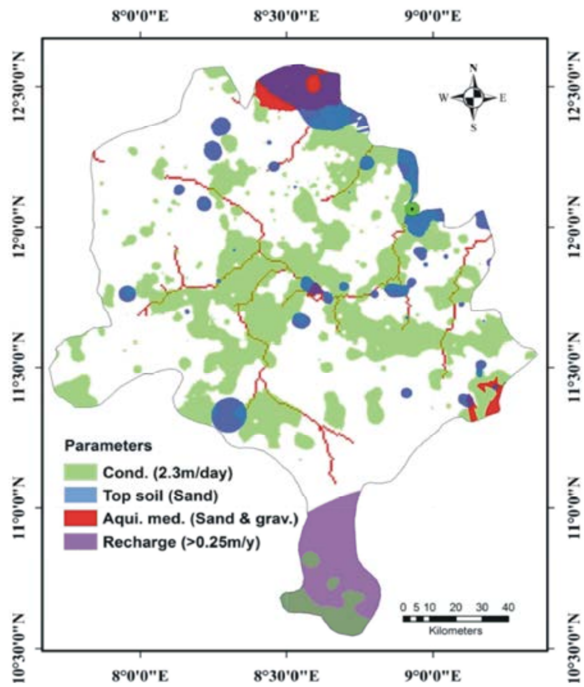

Fig. 13: Conductivity, soil type, recharge and aquifer media relationship

to 100% as shown in Table 4. Relationship between conductivity and recharge was 45.21% being the least. This further explained the fact that the conductivity of the study area is mostly controlled by 'alluvial well depletion' effect. Furthermore, the 60.79% of the entire most porous media (i.e. sand, available only within 6.84% of the area of study) is situated within area having good conductivity rate. The connection between conductivity and most pervious material characterising the aquifer media (i.e. sand and gravel, which is also available within only 2.82% of the entire study area), it was established that 82.38% of it falls under area recording good conductivity rate.

When comparison was made between parameters, it was established that there is 100% connection between areas with high recharge and soil media. On the other hand, it was also recognized that there exists identical relationship of 69% between area covered by aquifer media against recharge and soil media.

Conductivity and No Yield Zone Relationship: Since low yield in wells may be as a result of low hydraulic conductivity of the formation of the nearby surrounding area of the borehole (which is also associated with specific capacity, transmissivity and hydraulic conductivity). Again, being that the well yield is considered an acceptable and reliable statistical test validator for a comparative study of the hydraulic systems in different hydrogeological locations; a test was carried out in this study to ascertain the relationship between conductivity and delineated areas with poor and/or no yield. This is achieved by superimposing the delineated poor and/or no yield zone and the conductivity maps as shown in Fig.14. However, the latter map was analysed at various levels of conductivity rates with a view to establishing a clear relationship at varying conductivity levels.

Table 5: Conductivity and no yield zone relationship

		Conductivity-no/poor yield relationship	
Conductivity (K) (m/day)	Percentage area cover (%)	Connection (%)	No connection (%)
2	46.28	25.74	74.26
2.3*	35.17	10.53	89.47
4.3	8.11	3.31	96.69
8.6	1.21	0.36	99.64

*Average for the entire study area

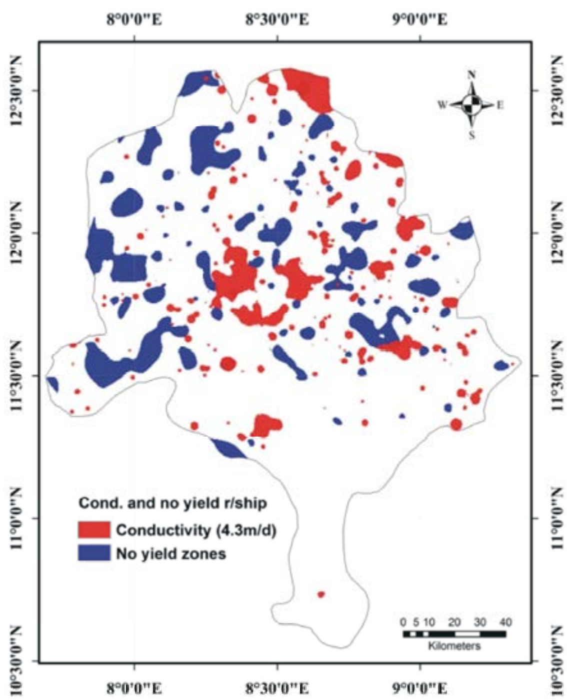

Fig. 14: Conductivity and no yield zone relationship

Table 5 highlighted that the level of connection between the maps is decreasing with increasing level of conductivity rate. The entire level of 'no connection' is between 74.26-99.64%. This has further endorsed the fact that there is a strong association between yield and hydraulic properties within well vicinity.

CONCLUSION

Although, at the moment only a few stream aquifer analysis tests have been documented in the literatures, it was established in this study that GIS-based spatial analysis can be employed to effectively assess 'alluvial well depletion'. Furthermore, the GIS can also used to successfully determine the spatial relationship between aquifer parameters. It was established that area with highest conductivity is generally characterised by the alluvial well depletion effect and groundwater flow pattern is not only controlled by the structure of the water table but also by the distribution of hydraulic conductivity. In addition, no association was found to exist between steep slope and conductivity (indicating the negative effect of slope vis-à-vis conductivity) and very strong connection occurs between areas with high recharge and soil media. Relatively high association was evident between aquifer media, recharge and soil media. These apart from validating the data quality have also endorsed several theoretical assertions. Moreover, Proper management of groundwater resources through accurate estimation of groundwater hydrogeologic parameters is exceptionally crucial. Absence of proper hydrogeological base maps and poor knowledge of geology have beleaguered the practice of hydrogeology in Kano state, Nigeria, this study will go a long way in aiding researchers of groundwater management in the state. It was established that the Transmissivity of the wells within Kano is from 8.5 to 1068 m^2/day, Specific Capacity from 0.4 to 565m^2/day. Hydraulic Conductivity (saturated) is typically 0.1-41m/day, Recharge rate is 0.1- 0.6m/year, well yield is from 4 to 145 m^3/day, Drawdown 0.1-44m, depth of saturation from 6.24 to 122m, Static water level from 1.2 to 43m, while the average rainfall is from 629-1508mm.

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