Aquifer potential of the transboundary crystalline-sedimentary complexes: from Northcentral Nigeria to Northwestern Cameroon border

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ABSTRACT
The aquifer system was apparently hidden but has been revealed as linked to transboundary aquifers; hence, additional info for data update of the International Groundwater Resources Assessment Center (IGRAC). The aquifer was explored for the purpose of Internationally Shared Aquifer Resource Management (ISARM). It advanced from fractured aquifers at upstream to the multi layered aquifer system toward downstream. The watershed was explored from Northcentral Nigeria to Cameroon border with electrical sounding. Geological/ Hydrogeological details were locally concentrated at the center of the watershed via drilling program, aquifer tests, and hydrological modeling. Aquifer stress index (AQSI) of the region was reviewed from the existing global dataset. Results revealed aquifer provenances from crystalline and sedimentary complexes. The aquifers were relatively inferred at third and fourth geoelectrical layers at upstream and downstream, respectively. Generally, drilling operation showed depth as ≥50.0 m. Most boreholes showed drawdown of ≤5.0 m and transmissivity of ≥100 m²/day, signifying the prolific nature of the aquifer system and enormous groundwater recharge. The AQSI ≤ 0.1 signified a stress-free aquifer. Concentrations of solutes are within nutritional background, yet moderately hard with bicarbonate/carbonate concentrations that can degrade the irrigation quality. Precipitates (CaCO₃) from limestone provenance may hamper borehole yields at downstream alluvium. Thus, injection of gypsum at the groundwater recharge zones is a certified remedial.

Introduction
Growth in population, urbanization, industrialization, as well as production and consumption of goods have necessitated increasing supply of freshwater resources (WWDR, 2015). In the freshwater supplies, transboundary aquifers (TBAs) play significant roles in socio-economic development (Lee, Jayakumar, Shrestha, & Han, 2018). Even when the size is small (Puri & El-Naser, 2002) like the aquifer system studied, it would still satiate the increasing demand for safe groundwater utilization. This is because groundwater supply is considered as low cost and climate-resilient option that can meet the rapidly growing freshwater demand (Taylor, 2015), particularly in regions of intensive economic activities, like the northerncentral Nigeria axis of Benue Trough. The region is an extensive watershed that stretched to Northern Cameroon (Figure 1A). Identifying such an aquifer of transboundary potential is important for the purpose of Internationally Shared Aquifer Resources Management (ISARM), especially now that some weather variables like mean temperature and rainfall have been altered by Climate Change. For instance, the global temperature had increased to 0.4°C in the last century and now up to 8°C, yet the Intergovernmental Panel on Climate Change (IPCC, 2014) projected further increase toward the middle of the 21st Century. Consequently, mean precipitation was expected to decrease at mid-latitude and sub-tropical dry region. For the fact that Nigeria is located between the tropical wet and dry regions (Eriksen, O’Brien, & Rosentrater, 2008), the entire countryside is vulnerable to the climate change (Idowu, Ayoola, Opele, & Ikenwe, 2011) with rainfalls becoming unpredictable and unreliable in timing and volume. Thus; incidence of drought worsens (Farauta, Idrisa, Egbulu, & Agu, 2011) and groundwater levels get lowered, especially around low storage basement aquifers (Ministry of Water Resources (MWR), 2013) even as most surface water systems dry up (Akpodioaga & Odjugo, 2010). More so, exacerbating constraints on the availability of surface water for irrigation are a growing concern (FAO, 2008). Apart from possible adverse impact on aquatic biomasses, the dry period mostly occur during flowering or development stages of crops, leading to low production of food and consequent downsides in the economy. For this reasons, some farmlands have been abandoned.

It is pertinent therefore to provide information on alternative water supply, mainly on groundwater development. This study reviewed some of the components of the Transboundary Water Assessment Program
TWAP) named by IGRAC (2014) as follows: groundwater, river basin, and lakes/reservoirs. Although IGRAC provided an excellent platform to exchange ideas and information on the transboundary groundwater resources in the west and Central African regions, there are still hidden information about untapped transboundary water system in Africa. Therefore, this study has unlocked huge amount of data to support TWAP. This is because the TWAP program has served as a cooperative event for background data information that can enable development and maintenance of any transboundary aquifer (TBA). Documentation of this data in public information domain for aquifer management strategies will eschew poverty, which IGRAC (2015) had related to lack of attention to TBAs, and hence can facilitate conditions for sustainable freshwater supplies across lifeline sectors, like agriculture, industries, and households.

Currently, only 5% of the Africa’s potential water resources have been developed (World Water Development Report, WWDR, 2015) due to lack of existing data to anchor strategic management
Groundwater recharge in the Watershed was estimated to be about 18.6 billion cubic meters [Japan International Cooperation Agency (JICA), 2014]. This watershed is enclosed by an international water divide that stretched from Northern Cameroon, bypassing Gboko area to Udi plateau hydrological center of the southeastern Nigeria (see Figure 1A). The water divide demarcated the lower Benue hydrological basin from Cross river basin up to the edge between lower and middle Benue Trough at Gboko; where it shifted westwards and connected to the ridge associated with the Charcot fracture zone (Nwajide, 2013). Topographic highs donated the catchment edge from the northwestern Cameroon to Benue Trough ridge belt. The axial NE-SW ridge belt was displaced between Gboko and Markurdi by a transform fault (Whiteman, 1982) with Keana Formation forming hanging block toward northeast of Markurdi area, whereas the Asu River Group formed the foot wall block toward southwest of Markurdi near Gboko. Limbs of the anticline are gentle, dipping up to 18 ± 2° and about N75°E strike orientation. Generally, the region is mainly covered by superficial sandy loamy soil (see ESM no. 31), which supports food cropping. The soil type may account for the ephemeral green vegetation and scanty tall trees that have been defined as Guinea savanna rain forest of the tropical climatic zone.

Geological, hydrological, and physiological background

Geology of the Northcentral Nigeria comprises a crystalline basement complex of Precambrian era and basin-filled cretaceous sediments. The crystalline rocks are undifferentiated (Offodile, 2002) but dominated by migmatite-gneiss (Obaje, 2009) as major litho-petrological components. In the early Cretaceous era, particularly during the Albian age, there was South Atlantic sea-level rise. The rise in the water level created hydrological slope toward Benue Trough, leading to transgression and deposition of marine sediments across the trough. These sediments are dominated by the lower cretaceous Asu River Group (Nwajide, 2013). Around the middle (central) portion of the trough, the sedimentary Group comprised Arufu, Uomba, Gboko, and Awe Formations. These formations are dominantly limestone deposits, especially in Gboko area (Adekeye & Akande, 2002) and shales. Regressive cycle opened sedimentation in the upper cretaceous era with Keana formation spanning from Cenomanian–Turonian to Coniacian periods, Lafia Formation of Campanian, Maastritchian ages (Akande, Hoffknecht, & Erdmann, 1992), and fluvial related alluvial sands of post cretaceous era (Adelana et al., 2008). These were restricted to middle Benue Trough with thickness ranging from 4,000 m (Obaje, Funtua, Ligouis, & Abaa, 1996) to greater than 5000 m toward the lower Benue Trough. The regional geology therefore affected the studied Watershed.

Geophysical survey

Information regarding depth, thickness, lithology, and areal extent of aquifer units was inferred via surface geophysical-vertical electrical sounding using a Schlumberger array. A resistivity meter of McOhm 2115A model was used for the investigation in 29 locations (see ESM from No 1 to 29) from the upstream of the watershed to the downstream area. The locations surveyed spread across latitudes 6° 34’ 07”N–8° 16’ 40”N and longitudes 8° 48’ 15”E–10°10’ 20”E. Spacing between two current electrodes (AB/2) was increased in steps from 1.0 m to the maximum of about 100 m, while the same number of potential electrodes were fixed and spaced as (MN/2) = 0.25 m between the current electrodes. Occasionally, the MN was increased (whenever the potential difference or voltage became very small to be read out) up to a maximum of 10 m (Ukpai & Okogbue, 2017). Precaution was taken to avoid features that generate artificial resistivity, like bridges and fences made of concrete or steel iron, tarred road, and flowing streams. In order to resolve 1D sounding curves for geoelectric units and corresponding depths, apparent resistivity data were subjected to an inversion method.
Figure 2. (A) Air percussion drilling method showing drilling in progress at BH 3 with dirty crystalline cores being packed (circled); (B1, B2 and B3) Outcrops of crystalline rocks (C) Washed cores appear as clean crystalline chips in a water filled washbasin. (The chipping was used for gravel packing in the sedimentary areas).

Figure 3. Iso resistivity map of the entire Watershed; (A) for the third geoelectric layer, $\rho_3$ and the (B) underlying fourth geoelectric unit, $\rho_4$. (Note: The axis marked “a” at the legend is the aquifer representative band).
via WIN-Resist software on log–log graph sheets. Resistivity for each groundwater prospective geoelectric unit was correlated in a modeled regional map.

**Drilling and pumping analyses**

**Drilling program**

Borehole drillings were conducted on fewer locations of the aquifer zones within latitudes 7° 05′N and 7° 35′N, as well as longitudes 8° 50′E and 9° 18′E around the central portion of the watershed, between upstream and downstream portions of the region. Due to non-uniformity of the Crystalline-sedimentary terrain, various drilling methods were used (ESM No.30). The rotary method was specifically used (see ESM no.31a) at areas underlain by alluvial deposits; however, at some depths where hard rocks were encountered, the drag bits conventionally used at such unconsolidated terrain were retrieved from the rig and replaced with a percussion diamond bit (Figure 3B; ESM 31b No.D). In this situation, the overlying unstable alluvium was stabilized by installing retrievable overburden stainless pipe across depth drilled with the rotary mud before resorting to the air percussion method. The affected boreholes were immediately cased (see ESM nos.31a {A1 and C1}) as the overburden pipes were being removed. Drillers’ logged data were acquired by coring during the drilling operation (Figure 2A). The cored data at aquifer zone was considered during proposal for screens slots and were designed with sufficient openings to minimize well loss during pumping (Driscoll, 1986). For this reason, the size slots covered greater than 40% of the circumference of the casing to maintain an entrance velocity within 3 cm/sec in order to keep friction losses negligible (Kruseman & de Ridder, 1991). The well screens were not industrial fitted but manually calibrated size slot perforation, which covers about 20 m of the total length of the casing pipes for each borehole. The boreholes were thoroughly surged (ESM no. 31a {A2, B, C2 and ESM No.32}) to remove residual drilling fluid (mud), cuttings, and other debris (Wurzel, 2001) in order to prevent viscous flow during the pumping test. Subsequent upon the surging processes, the boreholes were sealed (cork tightened) with PVC plastic cover and intermittently opened and closed after 24 hours for day-by-day measurements of static water levels (h0). The h0 was measured once in a day for about three (3) days, and the mean value recorded at each well (see ESM 33a-i).

**Pumping test analysis**

Prior to each pumping survey, the saturated zone was screened to about 90% in order to achieve full penetration of the aquifer thickness. According to Kruseman and de Ridder (1994), screening across the saturated part ensures maximum discharge from horizontal flow – a criterion that meets the basic assumption of flow to pumping wells. Flow rates were manually determined with respect to specifications of EPA (1995) by observing the time required to pump-fill a calibrated bucket of a known volume, after the Wells were surged for about one minute (see ESM No.33ii–iv). The constant rate method from single well approach was used in two phases, namely, (1) the pumping phase vis-a-vis submersible pump apparatus (1.5 HP) to generate data for drawdown (h – h0) and (2) recovery phase to produce data for residual drawdown (h – h0′) via spontaneous recharge. In order to produce reliable constant discharge, each pump was powered by a portable generator. Two parameters were monitored, namely, time (using stopwatch) and water levels in the wells using a dip meter. The drawdown was recorded on aquifer test data sheet (see ESM No 33(b-k)) as the difference between transient water levels during pumping (h) and the static water level (h0). The pumping test period lasted until pseudo-steady (or, equilibrium) state was attained; when the water levels in the well stabilized. The pump was turned off (ie shut down) and the recovery phase commenced immediately. The recovery water levels were timely observed and recorded and the residual drawdown (Δh) was evaluated with respect to h0 until the water level stabilized almost at the initial pre-pumping static water level (h0).

Based on the assumption that the transboundary aquifer is isotropic and homogeneous with infinite areal extent, drawdown (h–h0) and residual drawdown (h–h0′) versus log of time (log(t)) and log of time ratio (log(t/T)) respectively, were plotted on semi-log graph (Equations 1 and 2) via analogue computation, following Cooke, Rathod, and Rushton (1987) with respect to Cooper and Jacob (1946) standard graphical straight line approach, and thus

\[ h-h_0 = \frac{2.3Q}{4\pi T} \log_{10} t \]  \hspace{1cm} \text{Eq(1)}

\[ h-h_0' = \frac{2.3Q}{4\pi T} \log_{10} \frac{t}{T} \]  \hspace{1cm} \text{Eq(2)}

where t’ = time since the recovery commenced. Steady drawdown or drawdown per log cycle (Δh), as well as residual drawdown per log cycle (Δh′), were determined as equivalent to the gradient of the straight line, \( \frac{2.3Q}{4\pi T} \) (Hiscock, 2005), such that

\[ \Delta h = \frac{2.3Q}{4\pi T} \]  \hspace{1cm} \text{Eq(3)}

and

\[ \Delta h' = \frac{2.3Q}{4\pi T} \]  \hspace{1cm} \text{Eq(4)}

, and hence
\[ T' = \frac{2.3Q}{4\pi dh'} = Kb \]  
Eq(5)

(Fetter, 2007; Kruseman & de Ridder, 2000).

Then, a single parameter representing the physical property of both groundwater and the aquifer was calculated, and thus,

\[ K = \frac{T}{b} \]  
Eq(6)

Even aquifer productivity was evaluated as specific capacity

\[ S_c = \frac{Q(m^3/\text{min})}{\Delta h'(m)} \]  
Eq(7)

(Ted, 2005).

where \( b \) = aquifer thickness and \( K \) = hydraulic conductivity for the isotropic and homogeneous confined aquifer of indefinite lateral extent. This assumption has been frequently used as means of graphical solution method for the analysis of aquifer tests (Barlow & Moench, 1999).

The data set was subjected to comparative graphical analysis using AQTESOLV software version 9.0 (ESM No.34) for verification purposes.

To ensure precaution, the pumped water was discharged far beyond possible catchments of the pumped wells. The level of accuracy was significant at each location based on a negligible difference of about \( \leq 1.0 \) between \( \Delta h \) and \( \Delta h' \). Results of the recovery tests (the residual drawdown) were used for evaluation of the aquifer parameters in agreement with Michael, Khepar, and Sondhi (2011) due to the spontaneous nature of the test.

**Hydrogeochemical analysis**

Water sampling for geochemical analysis was designed at the end of each pumping test as follows: A pair of water sample was collected from each of the ten (10) sampled locations, using a plastic (one [1] liter) bottle, rinsed with filtered aliquots before sampling. One of the two samples was acidified with \( \text{HNO}_3 \) in each location to prevent precipitation of major cations, while the unacidified sample was for the analysis of anions. Films and suspended materials were filtered with micro-membrane filter paper (size: 0.45 \( \mu m \)), while the container was tightened after sampling.

Relevant parameters analyzed include electrical conductivity (EC), \( \text{pH} \), and total dissolved solute (TDS) as physical parameters; calcium ion (\( \text{Ca}^{2+} \)), magnesium ion (\( \text{Mg}^{2+} \)), sodium ion (\( \text{Na}^+ \)), and potassium ion (\( \text{K}^+ \)) as major cations; bicarbonate ion (\( \text{HCO}_3^- \)), sulfate ion (\( \text{SO}_4^{2-} \)), chloride ion (\( \text{Cl}^- \)), and nitrate ion (\( \text{NO}_3^- \)) as balancing anions; and others include florides (F), dissolved metals (comprising iron [Fe], manganese [Mn]), and coliforms. The EC, \( \text{pH} \), and TDS were measured in-situ using a portable WTW LF 90 Conductivity meter, whereas other chemicals were analyzed in the laboratory. The samples were collected based on the pumping test schedules and were transported to analytical laboratory at Benue State rural water supply and sanitation agency within 12 hours of collection. On arrival to the laboratory, the temperature of the samples was lowered to about 4°C in a refrigerator in order to prevent bacterial activities (Hiscock, 2005) and to limit degradation of nutrient species such as \( \text{NO}_3^- \) and \( \text{SO}_4^{2-} \). Aquachem software was used for graphical analyses of the data.

**Results and interpretations**

**Aquifer prospect**

Geophysical data showed about five geoelectric units represented with layer resistivities as \( \rho_1 \), \( \rho_2 \), \( \rho_3 \), \( \rho_4 \) and \( \rho_5 \) (Table 1) and somewhat corresponded with driller’s log. The drillers’ logs (ESM No.32) revealed local geological horizons generalized from top to the bottom as follows: dry alluvial; lateritized as red sand in some places as layer 1, finely grained sandstones and sandy clay as layer 2, shales locally fractured at contacts with underlying weathered limestone as layer 3, saturated alluvium intercalated by the sandy limestone for the fourth layer, and locally fractured bedrock zone/crystalline rocks as the fifth layer. Correlations of the driller’s logged units with the geoelectric layers are given as follows: layer 1 (or \( \rho_1 \)) was interpreted as overburden clastics; comprising the alluvial sands (ESM No.31d-A2) and some conglomerates (see Figure 2 (B1, B2)) both reflected high resistivities. The second layer resistivity (\( \rho_2 \)) was generalized as aquitards formed by well sorted, finely grained reddish sand with the facie changing locally to argillaceous nature around western flank toward boundary with lower Benue Trough. At this axis, the \( \rho_2 \) overlies shales of the third geoelectric layer (\( \rho_3 \)) locally fractured to produce isolated aquifers. It appears therefore that these local aquiferous units are mostly prominent from the Western to Northwestern flank near Gboko, as seen in the modeled iso-resistivity map (Figure 3A).

The fractured shales overlie weathered limestone and produced less prolific aquifer than the limestone aquifer, particularly at areas around Yandev. Outcrops of the limestone (Figure 2-B3) were observed around east of Yandev where it weathered and formed portion of the \( \rho_3 \) at downgradient area, producing aquifers along Boreholes (BH) 7, 8, 9 and 10 (Figure 4A). Comparing Figures 1B and 4A, it appears that the pressure heads are controlled by the topography. This is because sloping of hydraulic gradients (see Figure 4B) along the axis of the limestone aquifer coincided with down-dip trend of the elevation (see Figure 1B). Hydrological disposition of this nature indicates that the limestone aquifer possibly graded from \( \rho_3 \) and
Table 1. VES results showing layer resistivities ($\rho$), corresponding depths (d) and hydrogeological potentials.

| Inferred Aquifer unit and the corresponding, $\rho$ | Layered $\rho$ in $\Omega$m | Thickness (m) | Drilled |
|--------------------------------------------------|-----------------------------|--------------|---------|
| Aquifer Layered 1                                | $\rho_1$                     | 125          | ND      |
| Aquifer Layered 2                                | $\rho_2$                     | 107          | BH 2    |
| Aquifer Layered 3                                | $\rho_3$ & $\rho_4$          | 5.5          | ND      |
| Aquifer Layered 4                                | $\rho_5$                     | Nil          | ND      |
| Aquifer Layered 5                                | $\rho_6$                     | 170          | BH 7    |
| Aquifer Layered 6                                | $\rho_7$                     | 12.1         | BH      |
| Aquifer Layered 7                                | $\rho_8$                     | 45           | ND      |
| Aquifer Layered 8                                | $\rho_9$                     | 13.2         | BH 4    |
| Aquifer Layered 9                                | $\rho_{10}$                  | 3.1          | ND      |
| Aquifer Layered 10                               | $\rho_{11}$                  | Infinite     | ND      |
| Aquifer Layered 11                               | $\rho_{12}$ & $\rho_{13}$    | 16           | BH 1    |
| Aquifer Layered 12                               | $\rho_{14}$                  | 16.0         |        |
| Aquifer Layered 13                               | $\rho_{15}$                  | Nil          | ND      |
| Aquifer Layered 14                               | $\rho_{16}$                  | 16.0         | ND      |
| Aquifer Layered 15                               | $\rho_{17}$                  | 14.70        | BH 2    |
| Aquifer Layered 16                               | $\rho_{18}$                  | 6.2          | ND      |
| Aquifer Layered 17                               | $\rho_{19}$                  | 8.2          | ND      |
| Aquifer Layered 18                               | $\rho_{20}$ & $\rho_{21}$    | 3.2          | ND      |
| Aquifer Layered 19                               | $\rho_{22}$                  | 6.0          | ND      |
| Aquifer Layered 20                               | $\rho_{23}$ & $\rho_{24}$    | 8.2          | ND      |
| Aquifer Layered 21                               | $\rho_{25}$                  | Infinite     | ND      |
| Aquifer Layered 22                               | $\rho_{26}$                  | 12.2         | BH 8    |
| Aquifer Layered 23                               | $\rho_{27}$                  | 24.0         | ND      |
| Aquifer Layered 24                               | $\rho_{28}$                  | 20.0         | ND      |
| Aquifer Layered 25                               | $\rho_{29}$                  | 46           | ND      |
| Aquifer Layered 26                               | $\rho_{30}$                  | 12.2         | ND      |
| Aquifer Layered 27                               | $\rho_{31}$                  | 46           | ND      |
| Aquifer Layered 28                               | $\rho_{32}$ & $\rho_{33}$    | 3.6          | ND      |
| Aquifer Layered 29                               | $\rho_{34}$                  | 10.2         | BH 5    |
| Aquifer Layered 30                               | $\rho_{35}$                  | 24           | ND      |
| Aquifer Layered 31                               | $\rho_{36}$                  | 16           | ND      |
| Aquifer Layered 32                               | $\rho_{37}$                  | 1.8          | ND      |
| Aquifer Layered 33                               | $\rho_{38}$                  | 7.5          | ND      |
| Aquifer Layered 34                               | $\rho_{39}$                  | 8.0          | ND      |
| Aquifer Layered 35                               | $\rho_{40}$                  | 6.8          | ND      |
| Aquifer Layered 36                               | $\rho_{41}$                  | 13.30        | BH 11   |

Note: Aquifer is inferred at: resistivity ($\rho$) ≤ 200 $\Omega$m; depth (d) ≥ 20 m and thickness ≥ 10 m. ND = Not Drilled
dipped into a saturated alluvial deposit inferred as \( \rho_4 \). The alluvium was geologically confirmed as dominant deposit near the Transboundary Katsina-Ala River and formed the river bed. Provenance of the aquifer inferred at \( \rho_3 \) (see Figure 3A) also include Base flow at the weathered portion of the Basement from the eastern flank of the river. Contact of the limestone with the underlying Basement rocks was noted through the driller’s data (see ESM No.31C1 and C2), hence agreeing with Nwajide (2013) who noted that the limestone overlies the crystalline Basement rocks directly. The areal expression of the layered aquifer zones is delineated by green bands with \( \rho \) ranging from 200 to 600 \( \Omega m \) and marked with letter “a” in the legend (see Figure 3).

Thus, the local fractured shale and weathered limestone units formed a subsidiary aquifer system, though laterally located at different places but generally inferred at \( \rho_3 \) (or third geoelectric unit). The subsidiary aquifers are connected hydraulically to the N–S trending alluvial aquifer system suspected at \( \rho_4 \) (Figure 3B). For the fact that trend of the alluvial aquifer coincided with axis of the river bed, it is safe to deduce that the aquifer of the fourth geoelectric unit (\( \rho_4 \)) is transboundary. The alluvial aquifer reflected the narrow green band that trended North–South in Figure 3B. It stretched extensively from northwestern Cameroon to the north-central Nigeria where it opened to river Benue (compare Figures 1A and 3B). Generally, the aquifer units are represented in Figure 5A and B with pink color band, while the overburdens in \( \rho_1 \) and \( \rho_2 \) are represented with ash and dark ash bands, respectively. Depths to the geoelectrical aquifer units (Table 1, ESM Nos 1–29) varied slightly but can commonly be drilled to about 50 m (see ESM Nos.30, 32 and 33).

**Hydrologic interplay of the (water) resources**

Correlation of Figures 1B and 4A showed that a local groundwater mound overlapped with the edge of a regional fault trace at Gboko area. The mound is highly prominent around Yandev where it appears the watertable jutted toward ground surface; perhaps due to enormous recharge. It means that fractures associated with the fault node possibly streamlined groundwater to the weathered limestone aquifer, which stretched along line N–SE to discharge at the SE end (see Figure 4B) and into the alluvial aquifer, which eventually exports into the Transboundary River as depicted in Figure 4B. The figure revealed pressure heads of about 56.4 m and 50.5 m at the recharge and discharge zones respectively and significant head loss up to 150 m between the two.

*Figure 4. Hydrological map of the central portion of the watershed marked in Figure 3; (A) Potentiometric surface map in 3D showing the groundwater mounds (B) Configuration of the Hydraulic gradients along trend of Subsidiary Limestone aquifer.*
ends. The considerable head loss may have really being influenced by frictional energy loss from irregular flow path aperture from fractured shale to weathered limestone and through the alluvial deposit to the river.

Most of these fractures are sandwiched in the regional ridge system across Benue Trough (Zaborsky, 1998). Previously, it was reported that one of such ridge extended southwesterly from east of Keana (Onyedim, 2007) and crossed to south of River Benue as a ridge dominated by Crystalline rock fabrics (Ajayi & Ajakaye, 1986) like dots of igneous sills as represented in Figure 5A. But then, presence of sills indicates inherent fractures within the bedrock (Singhal & Gupta, 1999). Thus, offsetting of the regional NE-SW trending ridge belt (Whiteman, 1982) dislodged orientation of the embedded fracture pathway, as well as direction of groundwater flux toward Gboko through the NW-SE oriented fault trace which crossed the ridge. For this reason, it is suspected that the fractured shale-limestone aquifers are hydrologically linked to groundwater recharged from River Benue via fractures sandwiched in the ridge that had crossed the Benue River. The fractured shale-limestone aquifers have already been inferred at the 3rd geoelectric unit \( \rho_3 \), however, the limestone dipped into the saturated alluvium that constituted \( \rho_4 \) at the downstream around lower course of river Katsina-Ala. Connections of hydraulic pathways from the fault trace to \( \rho_3 \) and eventually to \( \rho_4 \), resulted in interflow between subsidiary aquifers (fractured shale-limestone-weathered crystalline regoliths) and the alluvial sands. It is suspected that the river Katsina-Ala recharges the crystalline aquifer at upstream via saturated alluvium that formed the river bed and vice versa at downstream axis. This hydrologic interplay is locally depicted across the NE-SW and SE-NW sections (compare Figures 1B and 5(A, B)) with flow pattern (see Figure 1B) signifying that the river is influent at the downstream. According to Schaller and Fan (2009), an influent river reflects groundwater exporter. Meanwhile, the Katsina-Ala River contributes much of the total groundwater potentials across Nigeria to the Watershed. This deduction is based on the average monthly statistical report released by Japan International Cooperation Agency (JICA) (2014) showing that the river discharges at rate of about 477 m\(^3\)/s by which 29% form groundwater potential of the Watershed from the upstream axis around Nigeria-Cameroon border. Thus, groundwater is imported and exported across the Watershed by the river at downstream and upstream areas.

![Figure 5. Modeled sections: (A) and (B) Respective modeled units along NW-SE and SW-NE crossed in Figure 1B; (A2) Groundwater flow net with respect to Figure 5A; (B2) Flow net with respect to Figure 5B](image-url)
respectively. Therefore, among factors that determine groundwater fluxes, like topography, geology and climate (Devito et al., 2005), topography and geology controlled configuration of pressure heads, hydraulic gradients and the groundwater flow direction in the studied Watershed (Compare Figure 1B, 4A, 5{A, B} and 5{A2, B2}).

Aquifer characteristics

Figure 6 [M, N, O, P, Q, R] presented drawdown curves that slanted out of the theoretical straight lines at early and intermediate periods of pumping in Boreholes (BH) that tapped the limestone aquifer, namely, BH 7, BH 8, and BH 9 along line N-SE. Such curve deflection beneath the straight line signifies aquifer loss. As seen in those figures, the drawdown curves returned to the standard (straight) line and further stretched to equilibrium after long period of pumping, possibly because the groundwater at that point was recharged at equal rate being discharged. Generally, about 80% of the boreholes surveyed, comprising Boreholes (BH) 2, 3, 4, 5, 6, 7, 8 and 9 showed drawdown limit of ≤ 5.0 m (Table 2). Krasny (1993) had stipulated the limit as conventionally within maximum acceptable range. Comparing the drawdowns with hydraulic parameters (like T, K) in Table 2, it appears the drawdown values decreased with increasing aquifer productivity (ie, specific capacity [S]). Thus, drawdown curves in those Wells penetrating prolific aquifers are approximately aligning uniformly along the theoretical straight lines (see Figure 6 [from C to R]). However, the curves at most cases are sinusoidal (see Figure 6 [from A to T]) with extrema ranging from local minima/or negative cycle (ie, deviation of curve below the theoretical drawdown) to local maxima/ or positive cycle (ie,
deviation of curve above the theoretical straight line). Curving amplitudes of this nature can be attributed to aperture contrast between different flow paths arising from dual hydraulic network (Jourde, Cornaton, Pistre, & Bidaux, 2002). Thus, flow between inter-phases like from a narrow fracture network to permeable intergranular media of inherent porosity was depicted by a change in drawdown amplitudes from negative cycle to positive cycle, respectively. These inter-phases include fractured clastics, alluvial sands and weathered crystalline rocks. According to Tijani, Crane, Upton, Ó Dochartaigh, and Bellwood-Howard (2018), the aquifer system of middle Benue Trough is formed by aggregation of intergranular matrix and fractures. Interphase between fractures and intergranular matrix marks possible change in flow-path aperture. According to Fetter (2007), varied aperture thickness can induce differences in the hydraulic characteristics.

The negative amplitudes were observed at the origin and intermediate parts of the curves and returned to the equilibrium in almost all the surveyed Wells (see Figure 6). It means that these Wells produced accelerated drawdown at intermediate time of pumping, perhaps when the drawdown influence had not connected prolific flow medium. At such a period, the measured field data curves (or actual drawdown) deviated beneath theoretical drawdown (represented in straight line curve). By implication, the water level in the casing was invariably lower than the water level in the aquifer after short duration of pumping when the pumped Wells were recharged from fractured media. But after longer period of pumping, the groundwater recharge probably connected the intergranular media (alluvial aquifer), then, the drawdown was retarded and equilibrium stage was reached; from thence, the amount of recharge equated the same rate discharged. At this equilibrium stage, the curves eventually returned to the theoretical straight line as the recharging flow.
transits from fractured shale and weathered part of the Basement rock to alluvium and/or solution influenced limestone; hence, gained profuse surging, consequent upon which gentle cone of depression would be created. According to Kruseman and de Ridder (2000), gentle (or flat) cone of depression is associated with pumping aquifers of high transmissivity. The studied aquifer system showed range of Transmissivity (T) magnitude from 20 to 586 m²/day and corresponds to regional water supply capacity in BH 2, BH5 (along the alluvial aquifer) and BH8, BH9 (along the limestone aquifer) where the value exceeded 100 m²/day (see Table 2). However, the minimum amount of the magnitude was observed at BH10 deciphered as discharge zone at the riverbed. This minimum is below conventional T of productive Well; perhaps influenced by principle of bank filtration—which can either inhibit flow into/or out of a river. The principle leads to decreasing riverbed hydraulic conductivity, K (Goldschneider, Haralampides, & MacQuarrie, 2007) due to formation of clogging layers (Schubert, 2006). Such situation was suspected locally at some portions where the alluvial aquifer is recharged by groundwater discharged from the upstream capture zone - formed by fractured shale and limestone aquifers. According to Hiscock and Grischek (2002), the quality of water gained via bank filtration (or speed at which the filtration occurs) strongly depends on subsurface capture zone. Therefore, clogging of intergranular spaces with fine solutes from the capture zone may have reduced the K around B10; resulting in the elevated drawdown during pumping (see Table 2).

In general, the groundwater recharge compensated the high discharge rate established to the range from 1080 to 1282 m³/day. This compensation initiated the equilibrium stance on the drawdown curves as seen at exit points of all graphs in Figure 6; possibly supported by the hydrologic interplay earlier supposed between the rivers and the aquifer provenances. For this reason, there is no amount of pumping that can stress the multi-layered aquifer system.
The aquifer stress index (AQSI)

Data for the parameters in equation [8] is not available locally, but the AQSI quantified based on national and international scales comprising the studied Watershed are available from WaterGAP (2012) dataset [ESM No.35]. Even so, eqn (8) was minimized to eqn [9] with condition that $F(x) \approx 1000$ Km$^2$; thus,

$$AQSI = \frac{W(x) - RF(x)}{R(x) - EF(x)} $$

(Doll & Fiedler, 2008; Doll et al., 2012)

$$AQSI = \frac{W(x)}{R(x)} $$

(Herbert & Doll, 2019; Lee et al., 2018)

where

- $x =$ areal coverage
- $F(x) =$ areal coverage function of the watershed under study: estimated to be $> 1000$ Km$^2$
- $W(x) =$ withdrawal rate within the coverage of $x$
- $RF(x) =$ return flow to groundwater due to irrigation or leakage across region $x$
- $R(x) =$ groundwater recharge rate within the region $x$
- $EF(x) =$ groundwater contribution to the environment within the region, $x$

The AQSI of the African continent (Figure 7) was extracted from the global representative dataset (see ESM 35). In view of the data analyzed across Africa, Figure 7 showed about 1000 mm/yr as $R(x)$ (see Figure 7A) and 5.0 mm/yr as $W(x)$ (see Figure 7B) for part of the continent that covers the region under this research. Then, with Eqn.9, the AQSI of studied watershed is about 0.005. This insignificant value is confirmed in Figure 7C by which AQSI ranged from 0 to 0.1 for the studied region. According to IGRAC (2015), AQSI $\geq 0.5$ (or 50%) signifies aquifer stress. Based on this fact, the result indicates negligible or no aquifer stress in agreement with Wada and Heinrich (2013) who reported earlier that TBAs in Africa are not yet stressed.

Chemistry of the water resource

Results of physico-chemical analysis (Table 3) showed that coliform bacteria was not detected, signifying the absence of bacteriological pollutants (Nigerian Standards for Drinking Water Quality, NSDWQ),
2015) even as pH is confined within slight acidity and alkalinity. Turbidity, though within standard limit but at alarm level around BH8 and BH9 earlier deciphered as recharge zone. According to Canadian Drinking Water Quality [GCDWQ] (2003), high turbidity level in groundwater indicates the presence of suspended solutes. Due to the turbid nature, the aquifer system may be vulnerable to habitation of micro-organisms and biocides, as well as heavy metals entrapment in future. Other physical parameters, mainly EC and TDS, range from 149 to 586 mg/l and 70 to 293 mg/l, respectively; hence, within freshwater limit, signifying mild concentrations of dissolved elements. Trend of major ions was generalized as: Ca$^{2+}$ > Mg$^{2+}$ > Na$^+$ for cations and HCO$_3^-$ > SO$_4^{2-}$ > Cl$^{-}$ for anions, indicating that Ca$^{2+}$ and HCO$_3^-$ controlled the ion contents in groundwater of the aquifer system. Dominance of Ca$^{2+}$ and HCO$_3^-$ in groundwater signifies proximity to recharge zone (Blanchette, Lefebvre, Nasteve, & Cloutier, 2010) as proved in graphical result (Figure 8A). The graph showed predominance of hydrogeochemical facie deduced at zone [i] of the figure [8A] as Ca-Mg-HCO$_3^-$, possibly arising from precipitation of CaCO$_3$ via high alkaline ions concentrations arising due to continuous loading from groundwater recharge source by the limestone aquifer. Thus, the reason of the elevated drawdown observed at BH10 may be related to fine precipitated solutes (CaCO$_3$), which may have clogged the intergranular permeability of alluvial sand around some boreholes at the downstream. Also, these solutes can encrust screen slot sizes, leading to low yield of affected boreholes. Panacea in this case is possible, either by declogging via injection of gypsum at recharge zone in order to provide source of soluble calcium that inhibit the solute precipitation, or by local reconstruction of the alluvium around circumference of the affected boreholes through periodic removal of the permeability-devastated deposits and replace with fresh permeable alluvial sands. According to Wang et al. (2020), such reconstruction process can improve filtration in sediments around riverbanks.

The absence of facies at other hydrogeochemical facie zones ii, iii, and iv (see Figure 8A) signifies dominance of calcitic minerals across provenances of the aquifer system, especially from the limestone axis; just as widespread contents of dissolved florides (F) and iron (Fe) showed groundwater contribution from the
| Sample Number | Location code | Flow rate, Q (m³/min) | Flow rate, Q (m³/day) | Drawdown (h – h₀) in meters | Residual draw -down (h-h₀)⁻¹ (m) | Transmissivity, T from pumping stage (m²/min) | Transmissivity, T due to Recovery (m²/min) | Hydraulic Conductivity (m/day) | Specific Capacity (m²/day) |
|---------------|---------------|-----------------------|-----------------------|-----------------------------|-----------------------------------|---------------------------------------------|------------------------------------------|-------------------------------|--------------------------|
| 1             | BH1           | 0.80                  | 1152.0                | 7.0                         | 7.5                               | 2.09 x 10⁻²                                | 30.11                                     | 1.95 x 10⁻²                  | 28.08                    | 1.8                      | 153.6                   |
| 2             | BH2           | 0.88                  | 1267.2                | 1.7                         | 1.5                               | 9.45 x 10⁻²                                | 136.1                                     | 1.07 x 10⁻²                  | 154.1                    | 7.7                      | 844.8                   |
| 3             | BH3           | 0.78                  | 1123.2                | 4.5                         | 4.0                               | 3.17 x 10⁻²                                | 45.65                                     | 3.57 x 10⁻²                  | 51.41                    | 2.6                      | 280.8                   |
| 4             | BH4           | 0.88                  | 1267.2                | 2.5                         | 2.5                               | 6.64 x 10⁻²                                | 95.62                                     | 6.64 x 10⁻²                  | 95.62                    | 4.9                      | 506.9                   |
| 5             | BH5           | 0.87                  | 1252.8                | 0.8                         | 1.5                               | 1.08 x 10⁻²                                | 155.8                                     | 1.08 x 10⁻²                  | 155.5                    | 7.8                      | 835.2                   |
| 6             | BH6           | 0.85                  | 1224.0                | 3.0                         | 4.0                               | 1.08 x 10⁻²                                | 55.97                                     | 3.89 x 10⁻²                  | 56.02                    | 1.3                      | 306.0                   |
| 7             | BH7           | 0.80                  | 1152.0                | 2.8                         | 2.8                               | 5.56 x 10⁻²                                | 80.06                                     | 5.56 x 10⁻²                  | 80.06                    | 4.0                      | 411.4                   |
| 8             | BH8           | 0.89                  | 1281.6                | 1.4                         | 2.0                               | 1.16 x 10⁻²                                | 167.5                                     | 8.14 x 10⁻²                  | 117.2                    | 5.9                      | 640.8                   |
| 9             | BH9           | 0.89                  | 1281.6                | 0.4                         | 0.40                              | 4.07 x 10⁻¹                                | 586.1                                     | 4.07 x 10⁻¹                  | 586.1                    | 36.6                     | 3204.0                  |
| 10            | BH10          | 0.75                  | 1080.0                | 12.0                        | 10.0                              | 1.1 x 10⁻²                                 | 16.46                                     | 1.40 x 10⁻²                  | 20.16                    | 1.0                      | 90.0                    |
| Minimum       |               |                       |                       |                             |                                   | 1.4 x 10⁻²                                 | 16.46                                     | 1.40 x 10⁻²                  | 20.16                    | 1.0                      | 90.0                    |
| Maximum       |               |                       |                       |                             |                                   | 4.07 x 10⁻¹                                | 586.1                                     | 4.07 x 10⁻¹                  | 586.1                    | 36.6                     | 3204.0                  |
Table 3. Results of Hydrogeochemical Analysis.

| Serial Number | Sample Code | pH  | Turbidity (NTU) | EC (μS/cm) | TDS (Mg/l) | Na (Mg/l) | K (Mg/l) | Ca (Mg/l) | Mg (Mg/l) | HCO₃ (Mg/l) | SO₄ (mg/l) | NO₃ (Mg/l) | Cl (Mg/l) | Total Hardness | Fe (Mg/l) | F (mg/l) | Mn (Mg/l) | Coliforms | Ca²⁺/Mg²⁺ |
|---------------|-------------|-----|-----------------|------------|------------|-----------|----------|-----------|-----------|------------|------------|------------|----------|---------------|-----------|---------|-----------|----------|-----------|
| 1             | BH1         | 7.2 | 2.0             | 186        | 93         | 100       | 6.0      | 21        | 14        | 95         | 27.4       | 12         | 9.0      | 110           | 0.01      | 0.05    | Nd        | Nd       | 1.5       |
| 2             | BH2         | 7.4 | 2.0             | 361        | 181        | 90        | 5.0      | 28        | 22        | 74         | 44.7       | 15         | 8.0      | 160           | 0.02      | 0.04    | Nd        | Nd       | 1.3       |
| 3             | BH3         | 6.9 | 1.0             | 412        | 206        | 75        | 3.0      | 24        | 14        | 86         | 15.3       | 08         | 7.0      | 117           | 0.02      | 0.07    | Nd        | Nd       | 1.7       |
| 4             | BH4         | 6.8 | 3.0             | 420        | 210        | 40        | 4.0      | 26        | 22        | 94         | 23.0       | 14         | 3.5      | 155           | 0.03      | 0.09    | Nd        | Nd       | 1.2       |
| 5             | BH5         | 6.9 | 4.0             | 274        | 70         | 80        | 6.0      | 24        | 16        | 76         | 18.7       | 15         | 8.0      | 126           | 0.02      | 0.03    | Nd        | Nd       | 1.5       |
| 6             | BH6         | 7.3 | 3.0             | 216        | 108        | 60        | 5.0      | 18        | 10        | 88         | 07.2       | 07         | 5.8      | 86            | Nd        | 0.08    | Nd        | Nd       | 1.8       |
| 7             | BH7         | 7.1 | 3.0             | 282        | 141        | 36        | 3.0      | 20        | 12        | 98         | 14.0       | 07         | 3.0      | 99            | 0.01      | 0.03    | Nd        | Nd       | 1.7       |
| 8             | BH8         | 7.2 | 4.0             | 586        | 293        | 60        | 6.0      | 24        | 14        | 117        | 13.0       | 03         | 6.0      | 117           | 0.02      | 0.05    | Nd        | Nd       | 1.7       |
| 9             | BH9         | 6.7 | 4.0             | 149        | 75.0       | 80        | 7.0      | 16        | 10        | 89         | 05.3       | 20         | 7.8      | 81            | 0.03      | 0.09    | Nd        | Nd       | 1.6       |
| 10            | BH10        | 6.8 | 3.0             | 431        | 225        | 120       | 8.0      | 20        | 12        | 74         | 17.8       | 6.0        | 12.0     | 99            | 0.02      | 0.07    | Nd        | Nd       | 1.7       |
| Minimum       |             | 6.7 | 1.0             | 149        | 70         | 3.6       | 3.0      | 16        | 10        | 74         | 5.30       | 03         | 04       | 81            | 0.01      | 0.03    | -          | -        | 1.6       |
| Maximum       |             | 7.4 | 4.0             | 586        | 293        | 120       | 8.0      | 28        | 22        | 117        | 44.7       | 20         | 13       | 160           | 0.03      | 0.90    | -          | -        | 1.3       |
| Nigerian Standards for Drinking Water Quality (NSDWQ) (2015) | | 6.5 – 8.5 | 5.0 | 1000 | 500 | 75 | 75 | 75 | 30 | 100 | 100 | 50 | 250 | 150 | 0.3 | 1.5 | 0.2 | 10 | - |

NSDWQ: Nigerian Standard Drinking Water Quality. Nd = Not detected.
igneous dominated (crystalline) part of the provenances. Such facie represents hard water (Ukpai et al., 2016), and with ionic ratio, $\text{rCa}^{2+}/\text{rMg}^{2+}$ greater than a unit at each location (see Table 3), the groundwater being represented is recharged from the surface water source (El-Aassy et al., 2015). Analogically, this would support the earlier deduction of hydrologic cycling of water resources around the watershed; from fluvial system (rivers Benue and Katsina-Ala) via fracture and matrix networks to groundwater regime, which flows back to the surface water body (Katsina-Ala River) through the alluvial riverbed. The hydrologic interaction involving the rivers and groundwater through the complex interconnectivity fracture-matrix pathways could have kept the aquifer system safe from stresses via continual replenishment of discharged or exploited groundwater. This characteristic can fast track transportation of solute contaminants (Medici, West, & Banwart, 2019), such as the CaCO$_3$. Meanwhile, prevalence of the single facie existed because; aquifer stress which can activate inert solutes is absent. The factors constituting the facie clustered within domain iv of the Durov graph (Figure 8B), signify an insignificant travel distance of the groundwater from recharge zone; hence, the flushing of the carbonate minerals from the parent rocks. Ukpai, Ezeh, and Effam (2020) noted that groundwater with considerable resident time could be characterized by uneven (or variable) hydrogeochemical facies. As seen in the figure, almost 100% of the factors were restricted in the domain (iv) belonging to the axis of ion exchange (Lloyd & Heathcote, 1985), which indicates recently recharged water (Ravikumar, Somashekar, & Prakash, 2015) that had not traveled far from the recharge source. The groundwater is generally

![Figure 7. Maps of Africa showing: [A] Average renewable groundwater between 1961-1990; [B] Water withdrawal as at year 2000; [C] Aquifer stress index (AQSI) in river Basins by year 2000 (Extracted from ESM 35).](image)
hard and hence requires minor treatment for industrial utilization; even as it will be unfit for irrigation of agriculture, particularly crop farming in future due to continuous loading of the CaCO$_3$ facie from the limestone provenance. According to Hiscock (2005), concentration of bicarbonate in water increases sodium hazards by precipitation of CaCO$_3$; a condition that attracts contents of toxic elements like boron and chloride which are injurious to sensitive crops.

**Conclusion**

Local integration of geophysical, geological, geomorphological, hydrological and hydrogeochemical studies determined potentials of aquifer zones, including the status as a transboundary aquifer (TBA). The TBA is recharged from the perennial fluvial system via fractures and intergranular networks that opened to alluvial riverbeds associated with transboundary Rivers Benue and Katsina-Ala. It comprised an alluvial aquifer that stretched North-South along the transboundary Katsina-Ala riverbed at downgradient, and subsidiary aquifer provenances formed by weathered regoliths from the crystalline basement complex, as well as fractured shale/limestone from the sedimentary basin at east and west up-gradients, respectively. Specifically, the riparian alluvial aquifer exports groundwater to the weathered regoliths at the upstream part of Katsina-Ala River and imports groundwater from shale-limestone aquifer at the downstream portion. The fractured shale-limestone opened to a groundwater recharge zone at the Gboko edge of a regional fault node, which diverts flow through the fractures embedded in the NE-SW Ridge Belt that crossed River Benue. Thus, the rivers replenish the aquifer system with equal or greater amount of discharged groundwater. For this reason, the TBA is stress-free as depicted in the magnitudes of transmissivity, which indicated regional groundwater potential.

Single hydrogeochemical facie across the area suggest little water-rock mixing, possibly due to short residence time. For this reason, concentrations of solutes are mainly within nutritional values. However, the groundwater is hard and can even impose sodium hazard in future due to continuous loading of calcium carbonate (CaCO$_3$) from the upstream limestone provenance. This carbonate compound is a fine solute, which migrates to downstream alluvial aquifer and concentrates or mars intergranular pores, and if not checked can devastate the soil texture against crop yields and even the aquifer structure against borehole yields. Injection of gypsum mainly at the recharge zone is suggested as major means of remediation in order to mop or dilute the fine solute precipitate. Generally, the aquifer system is potable, prolific, and transboundary in nature and, if developed and monitored periodically, can supply sustainable freshwater for utilization in economic sectors, like in industries, mechanized agriculture and domestic use.

**Disclosure statement**

No potential conflict of interest was reported by the author(s).
Funding

The author(s) reported there is no funding associated with the work featured in this article.

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